US006751367B2

(12) **United States Patent**
**Moslehi et al.**

(10) **Patent No.: US 6,751,367 B2**
(45) **Date of Patent: Jun. 15, 2004**

(54) **MULTIPLEXABLE FIBER-OPTIC STRAIN SENSOR SYSTEM WITH TEMPERATURE COMPENSATION CAPABILITY**

(75) Inventors: **Behzad Moslehi**, Mountain View, CA (US); **Vahid Sotoudeh**, Los Altos, CA (US); **Brian Kutner**, Santa Clara, CA (US); **Dario G. Falquier**, Palo Alto, CA (US); **Levy Oblea**, Union City, CA (US)

(73) Assignee: **IFOS, Inc.**, Sunnyvale, CA (US)

( * ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/422,146**

(22) Filed: **Apr. 24, 2003**

(65) **Prior Publication Data**

US 2004/0052444 A1 Mar. 18, 2004

**Related U.S. Application Data**

(63) Continuation-in-part of application No. 09/286,092, filed on Apr. 2, 1999, now Pat. No. 6,597,822.

(51) **Int. Cl.**[7] ............................ **G02B 6/00**; G01B 11/16

(52) **U.S. Cl.** ................ **385/13**; 250/227.14; 250/227.18

(58) **Field of Search** ............................... 385/10–13, 37; 250/227.14, 227.17–227.19, 227.23; 356/32, 35.5, 72

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,275,629 B1 * 8/2001 Eggleton et al. .............. 385/37
6,335,524 B1 * 1/2002 Udd et al. ............. 250/227.18

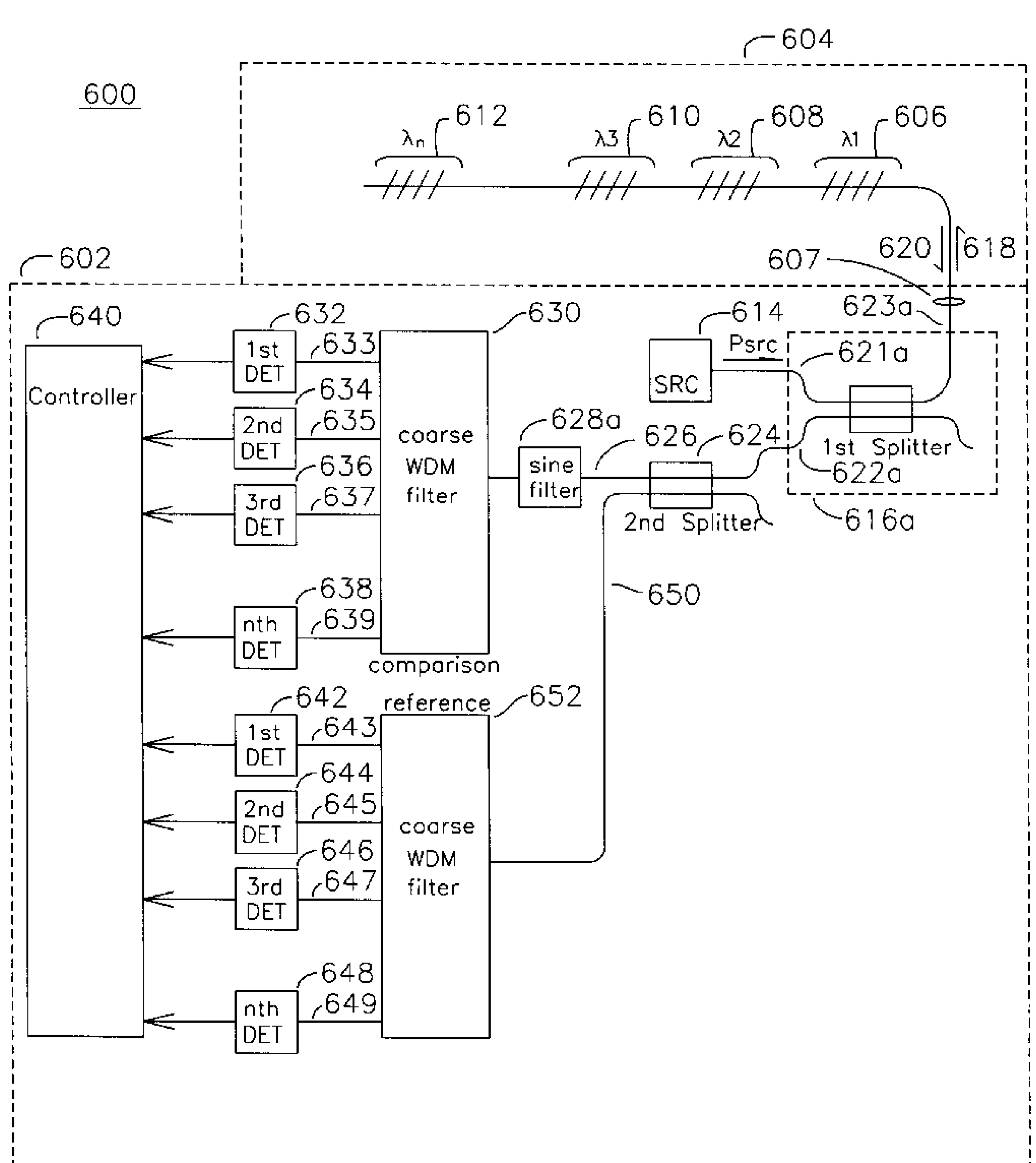
* cited by examiner

*Primary Examiner*—Frank G. Font
*Assistant Examiner*—Michael P. Mooney
(74) *Attorney, Agent, or Firm*—Jay A Chesavage

(57) **ABSTRACT**

A fiber optic sensor comprises two independent fibers having Bragg gratings which are coupled to commutating broadband optical sources through splitters and wavelength discriminators. The ratio of detected optical energy in each of two detectors examining the wave intensity returned to a wavelength discriminator coupled with the characteristic of the wavelength discriminator determines the wavelength returned by the grating. In another embodiment, tunable filters are utilized to detect minimum returned wave energy to extract a sensor wavelength Reference to the original grating wavelength indicates the application of either temperature or strain to the grating. In another embodiment, a plurality of Bragg grating sensor elements is coupled to sources and controllers wherein a dimensional change in a fiber having a Bragg grating is detected using a measurement system comprising broad-band sources, optical power splitters, a high-sensitivity wavelength discriminator, optical detectors, and a controller.

**16 Claims, 15 Drawing Sheets**



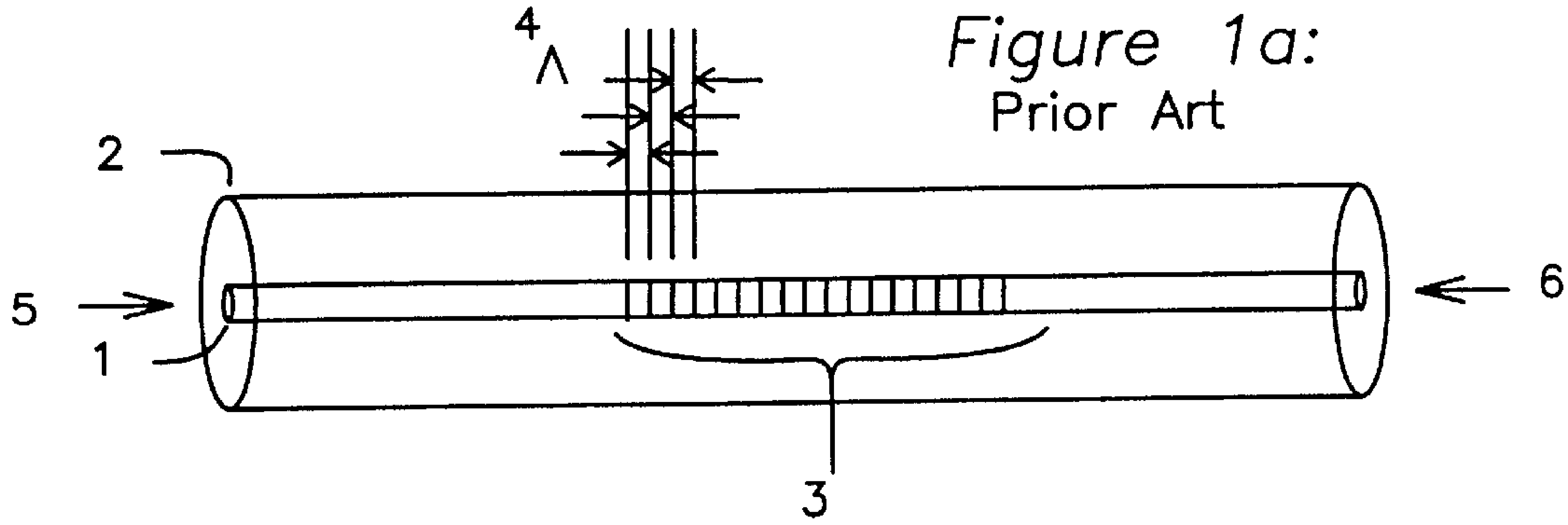



Figure 1a:
Prior Art

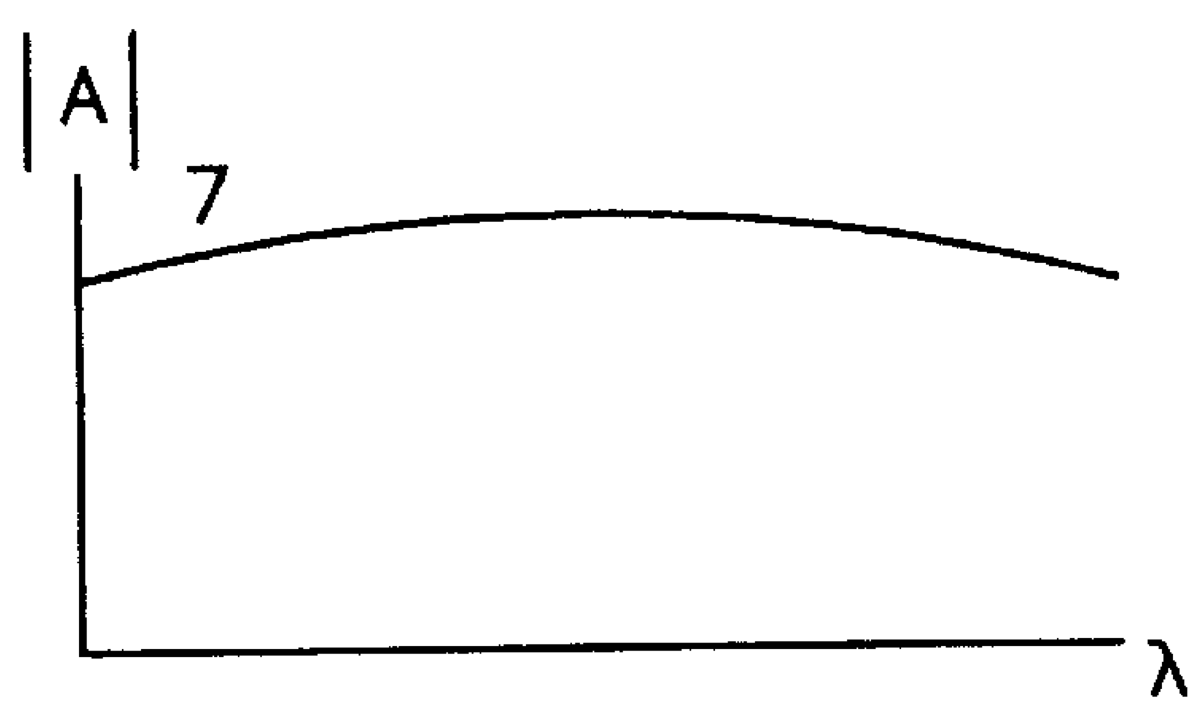



Figure 1b:
Prior Art

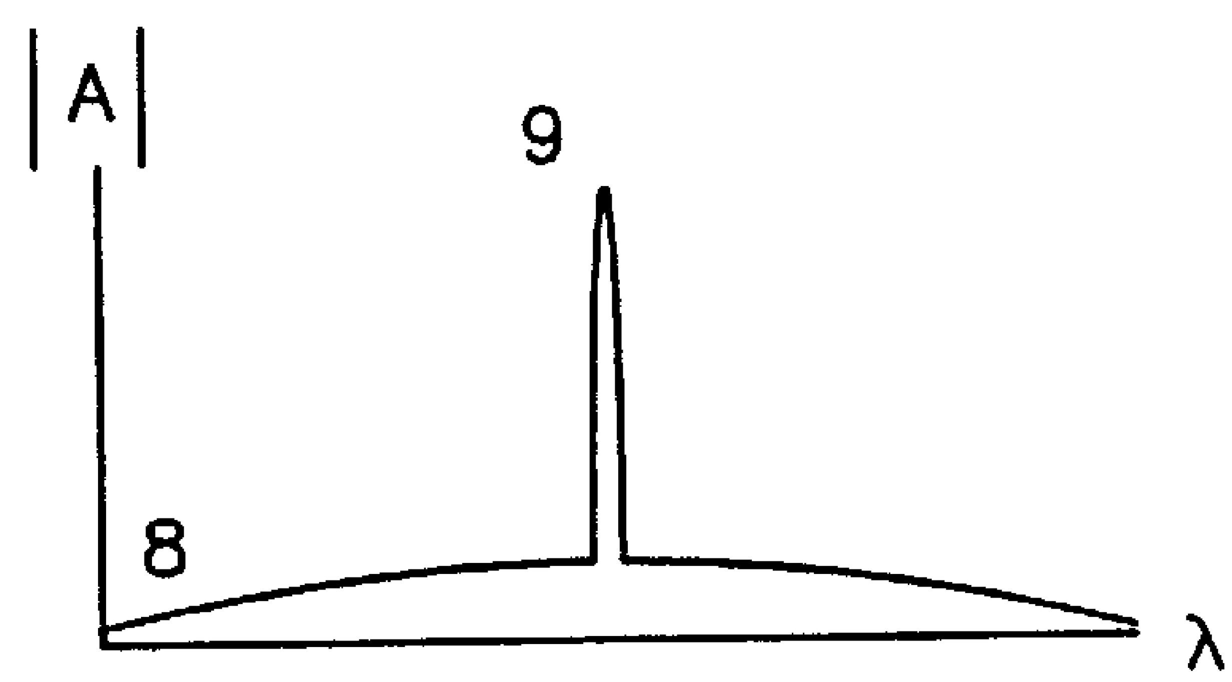



Figure 1c:
Prior Art

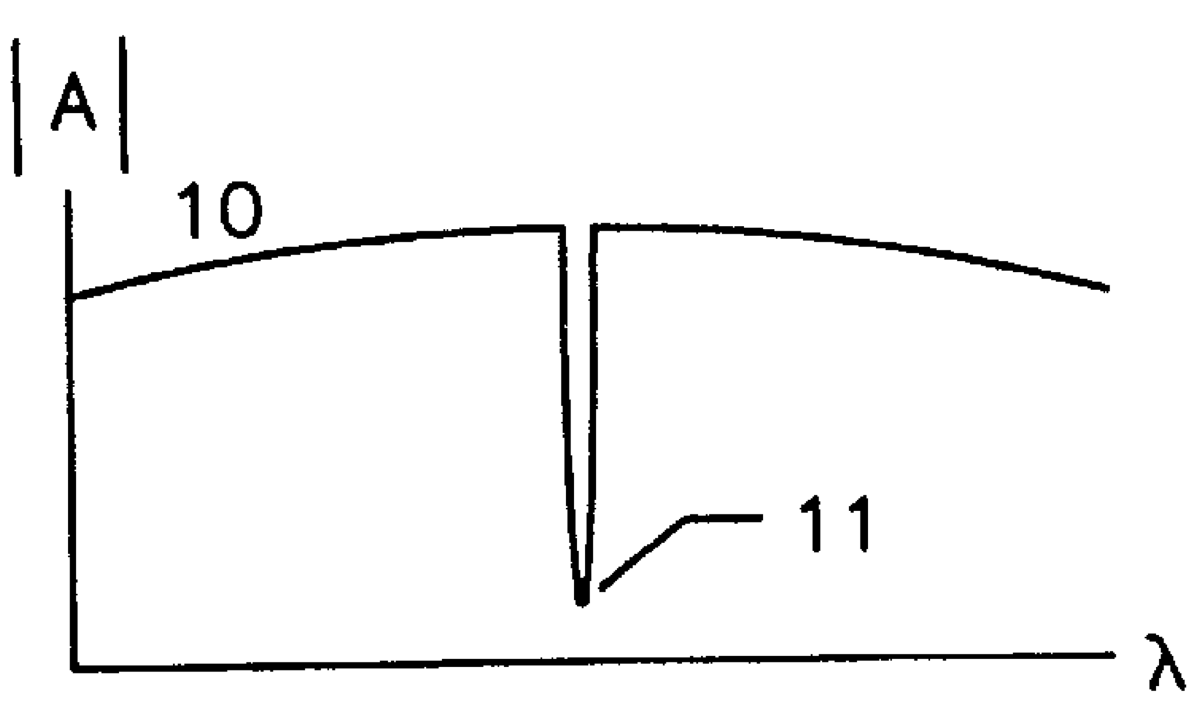



Figure 1d:
Prior Art

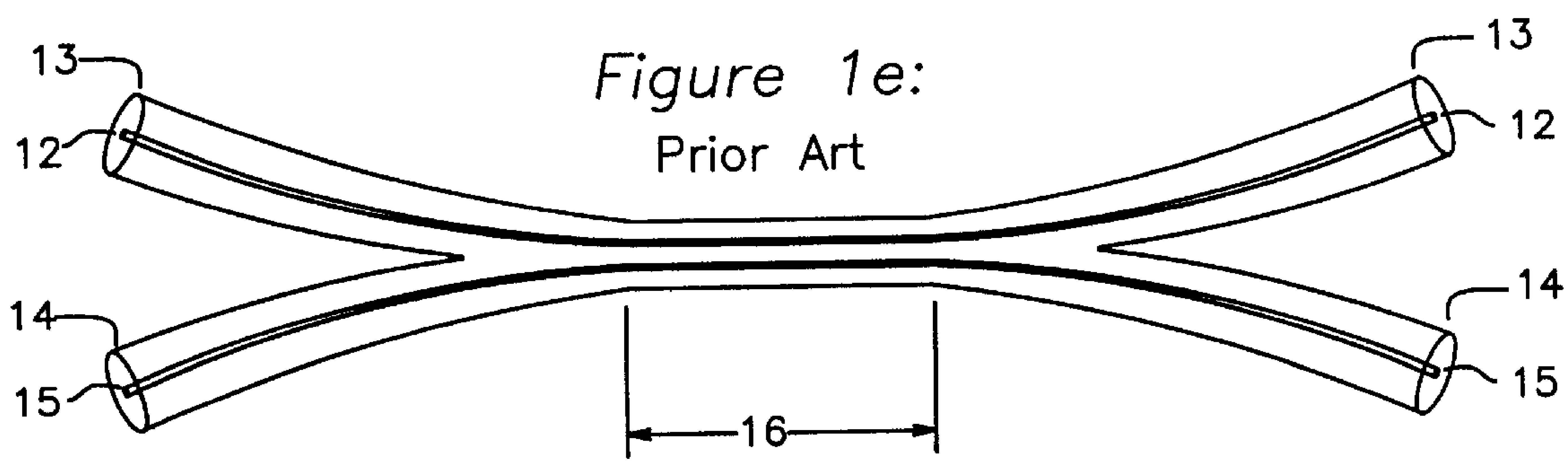



Figure 1e:
Prior Art

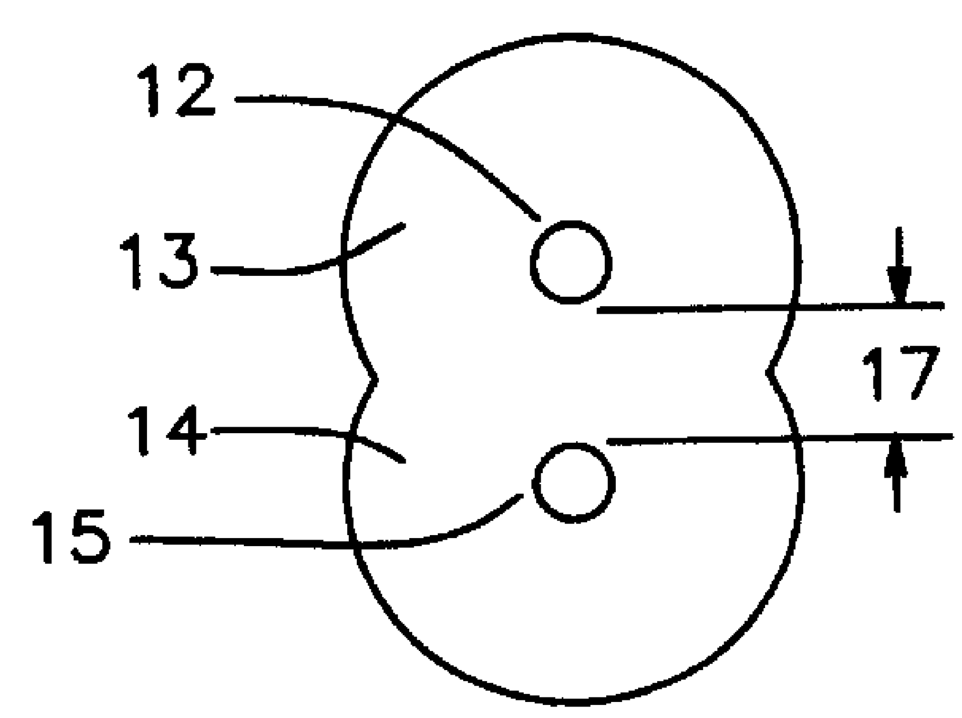



Figure 1f:
Prior Art

Figure 2:

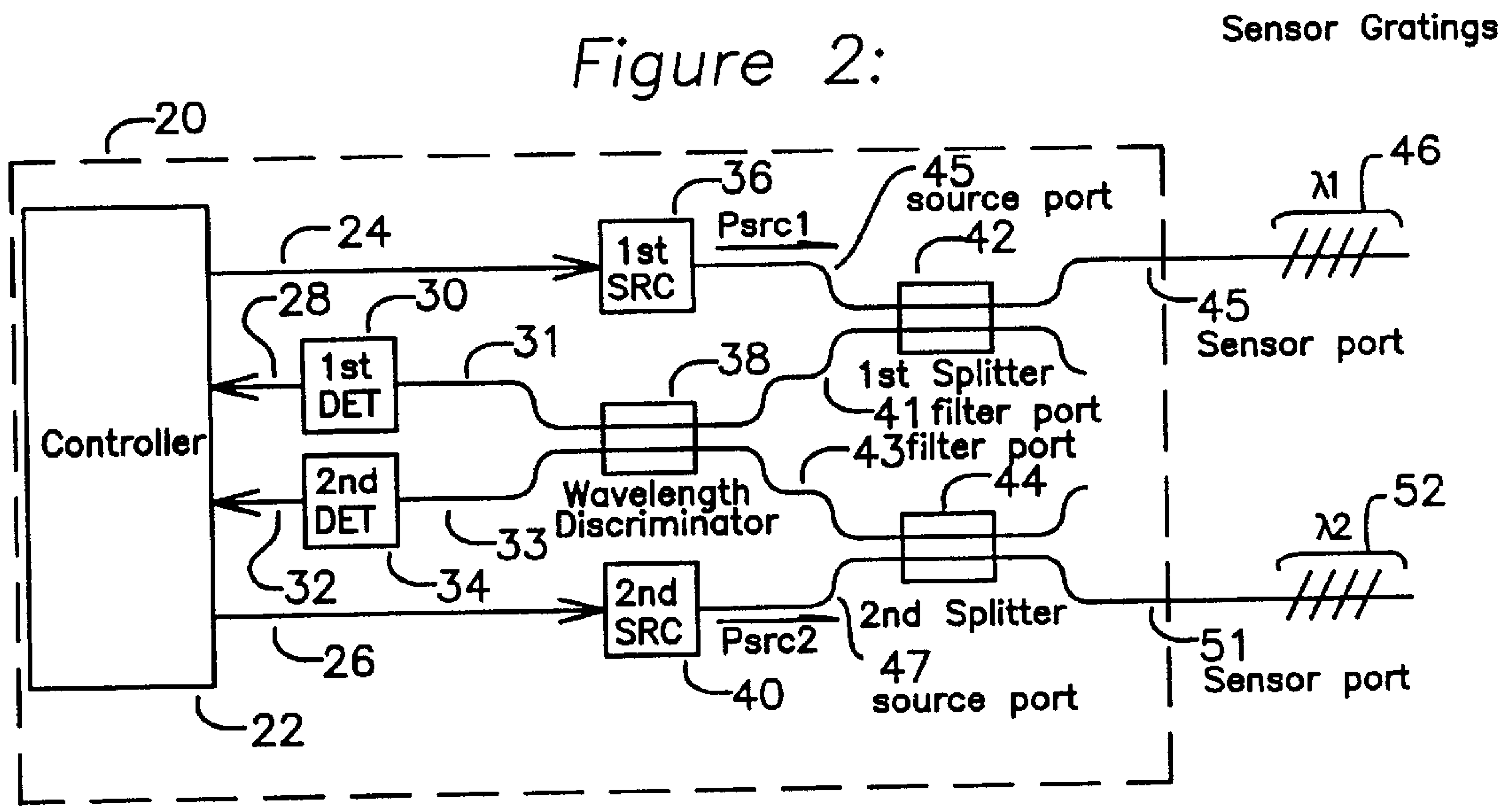



Figure 3:

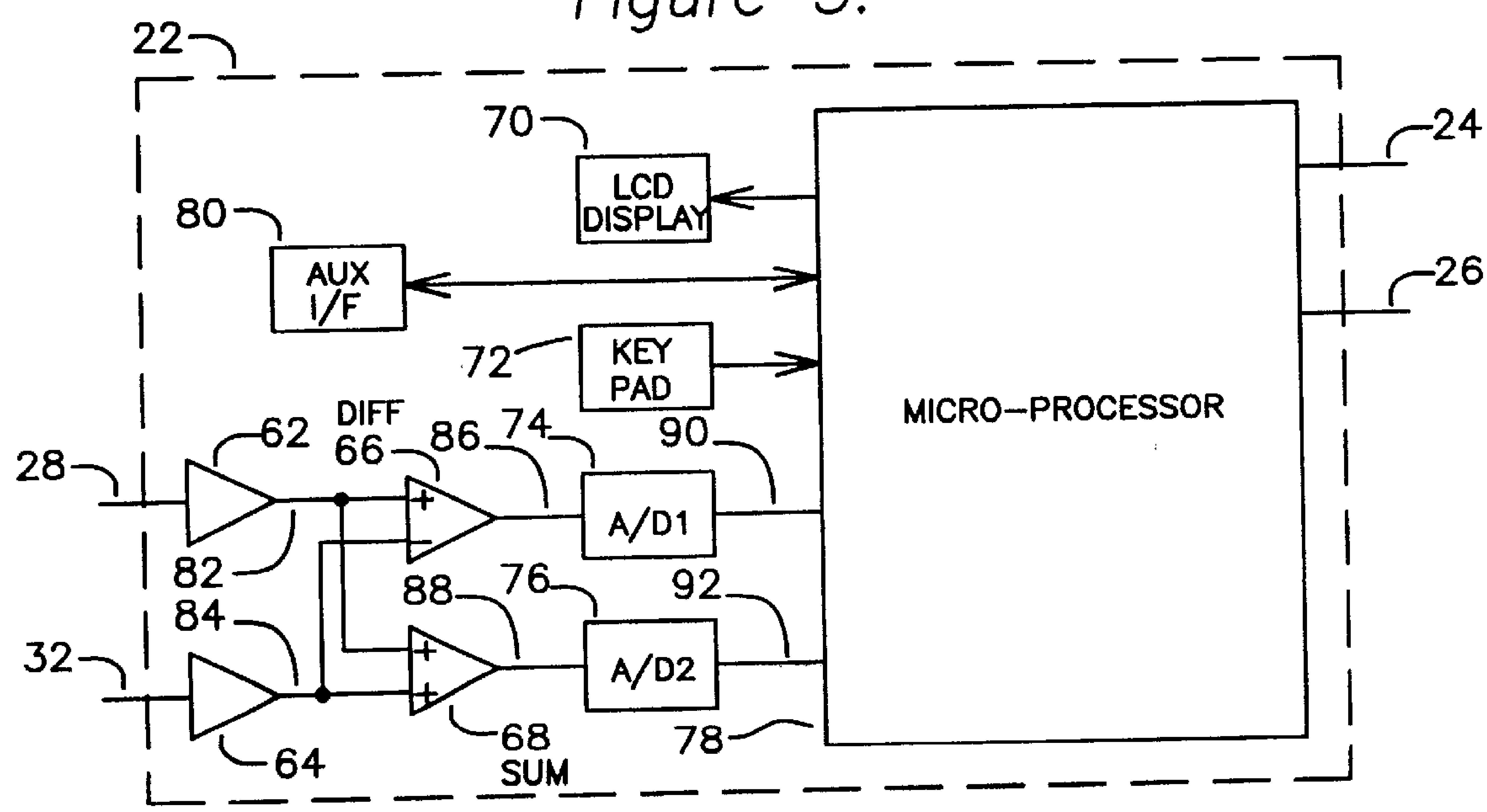


Figure 4:

Wavelength Discriminator

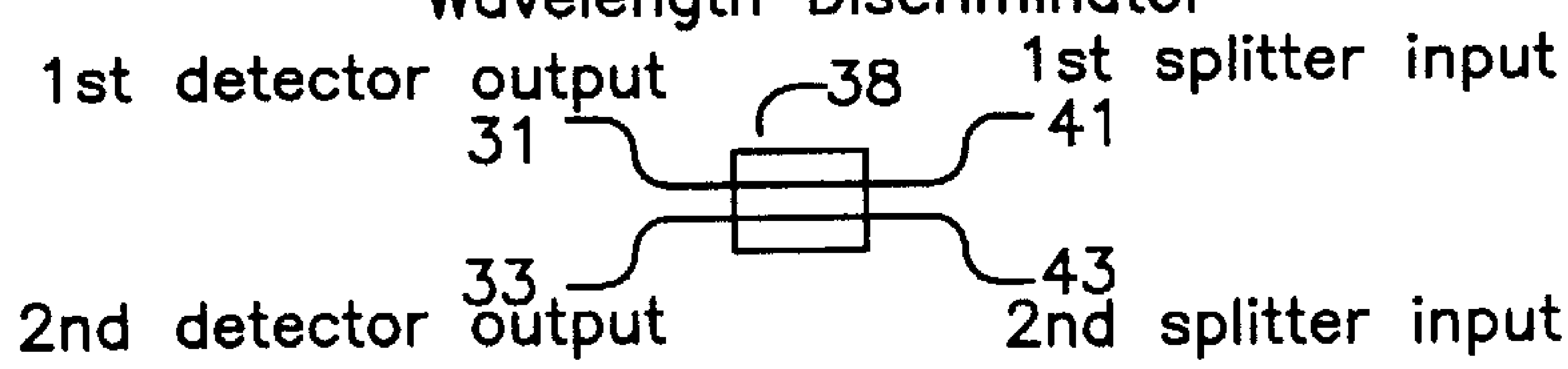



Figure 5:

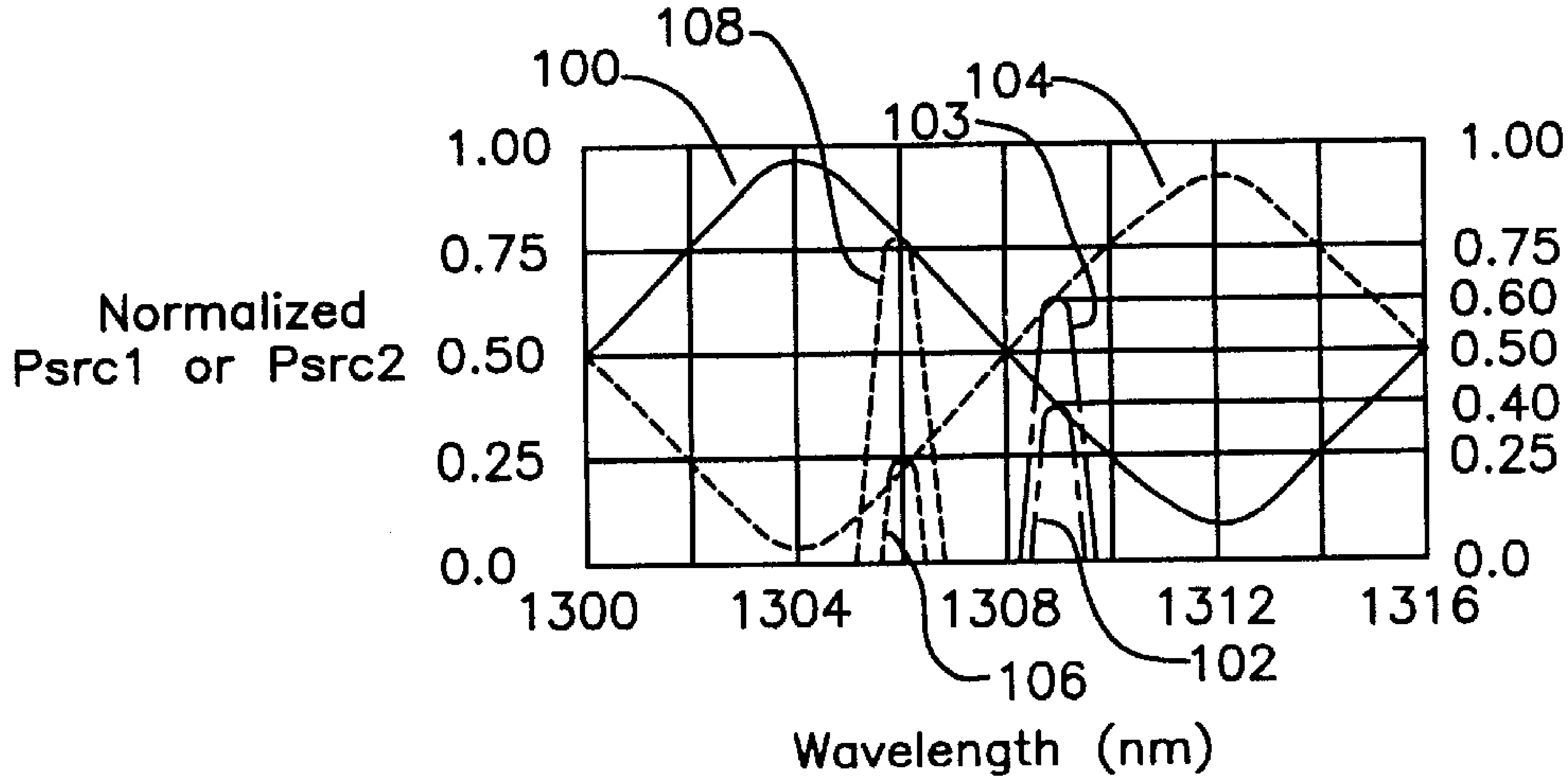



Figure 6:

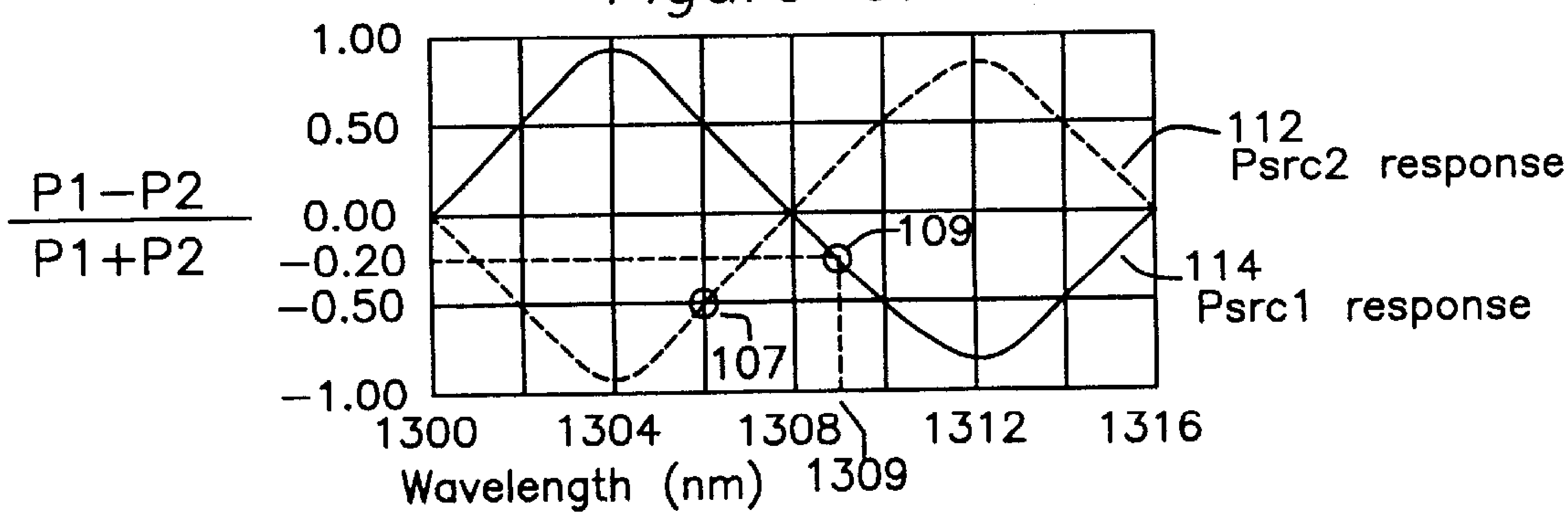


Figure 7:

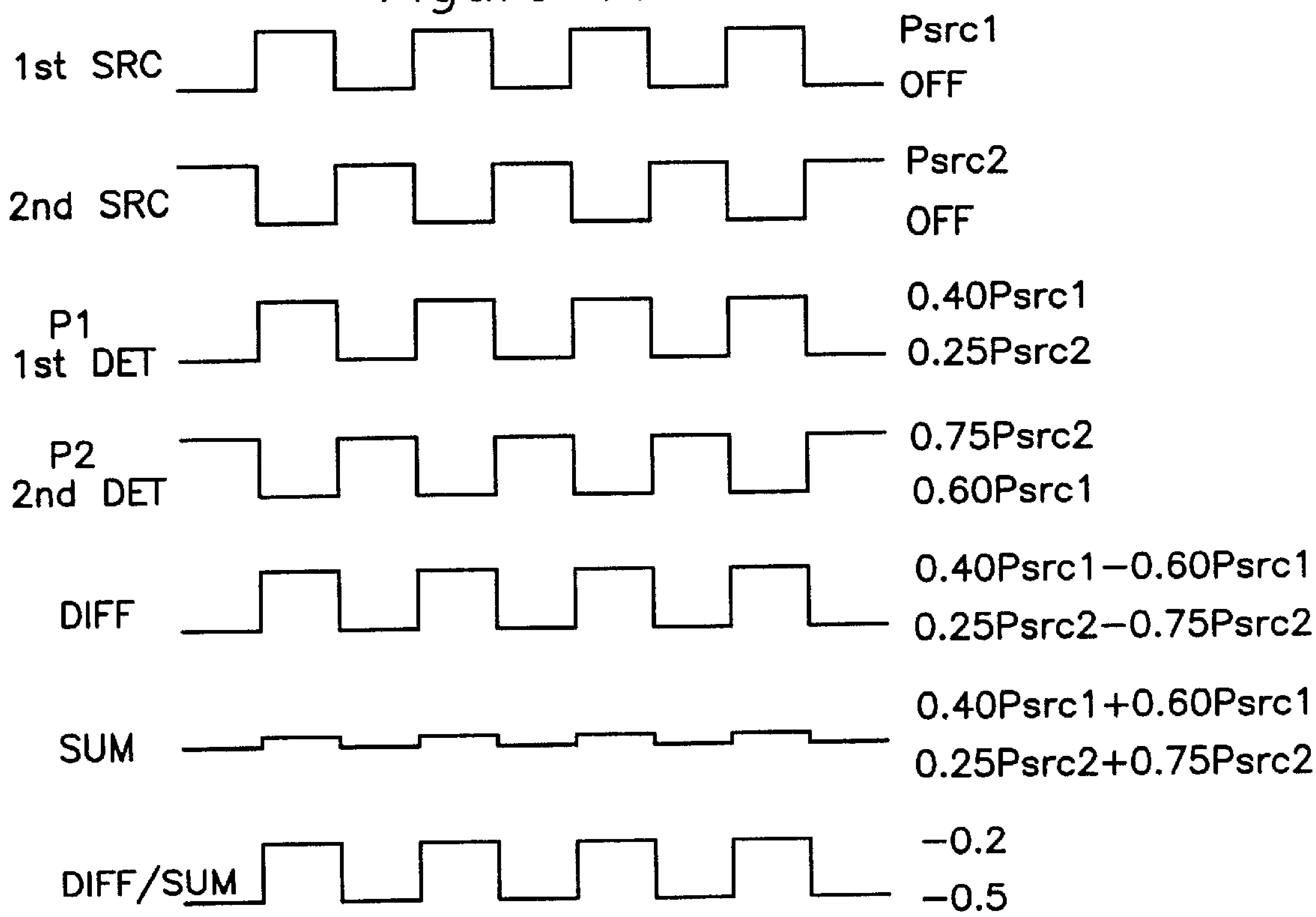

1st SRC
Psrc1
OFF
2nd SRC
Psrc2
OFF
P1
1st DET
0.40Psrc1
0.25Psrc2
P2
2nd DET
0.75Psrc2
0.60Psrc1
DIFF
0.40Psrc1−0.60Psrc1
0.25Psrc2−0.75Psrc2
SUM
0.40Psrc1+0.60Psrc1
0.25Psrc2+0.75Psrc2
DIFF/SUM
−0.2
−0.5

Figure 8:

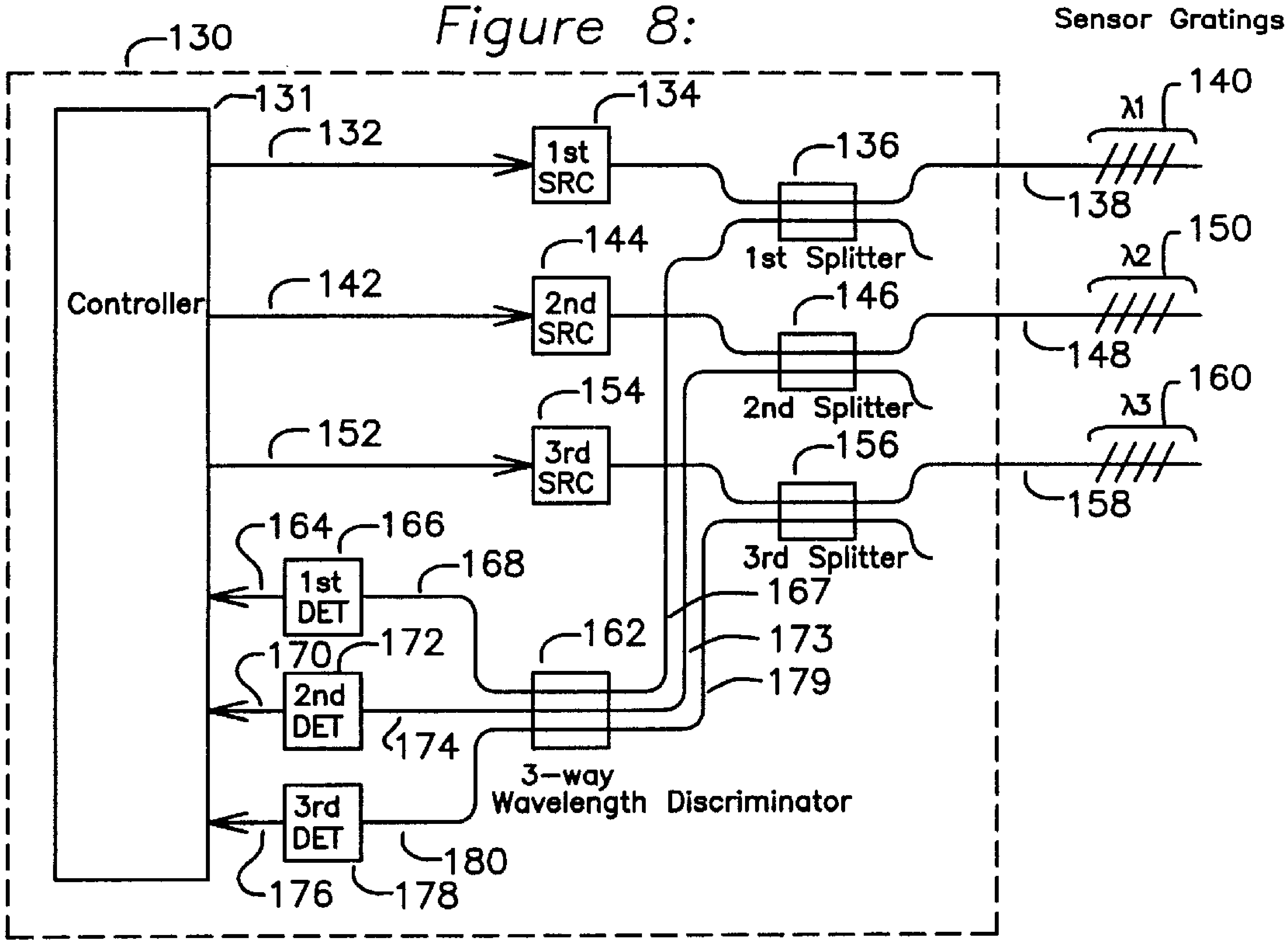



Figure 9:

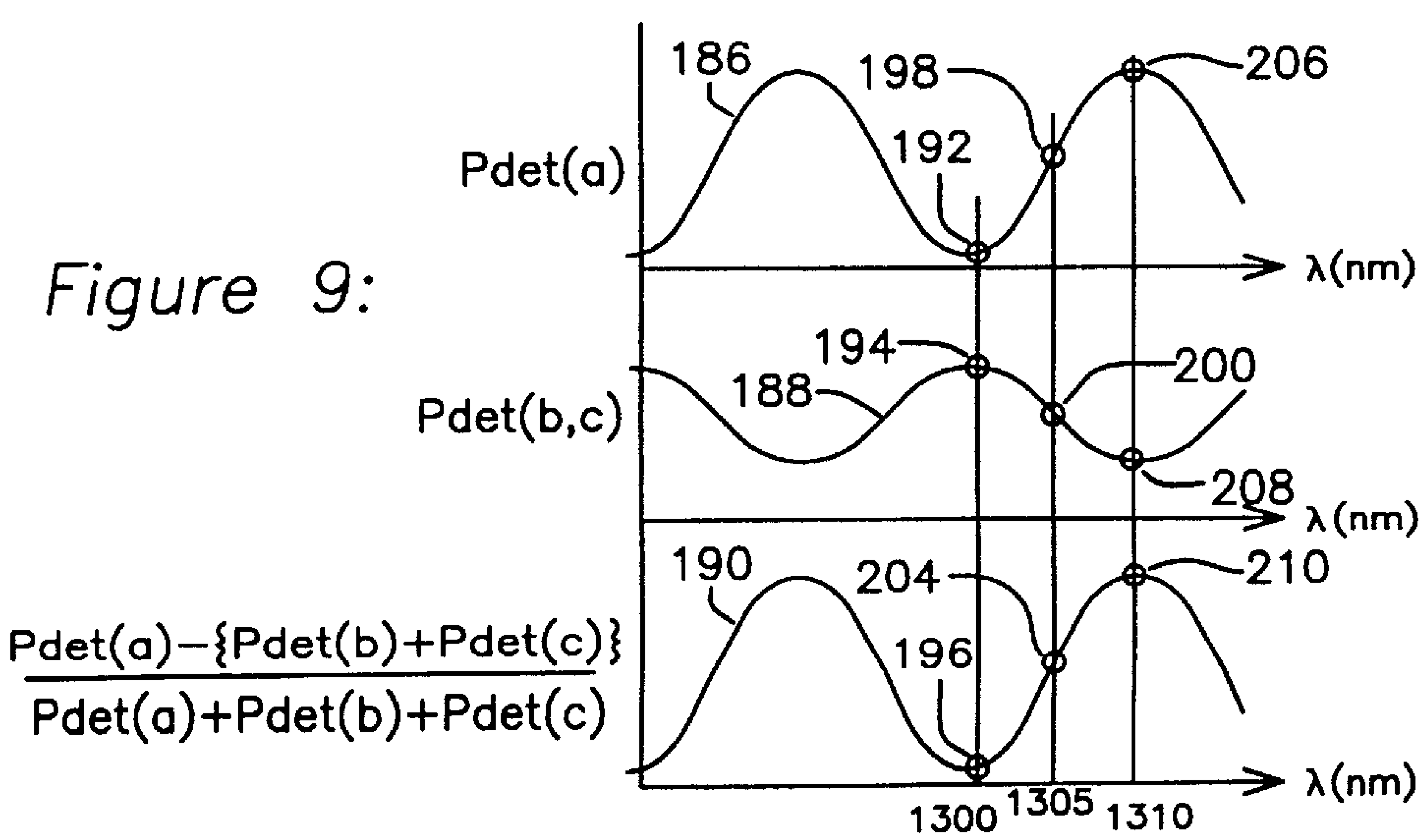


Figure 10:

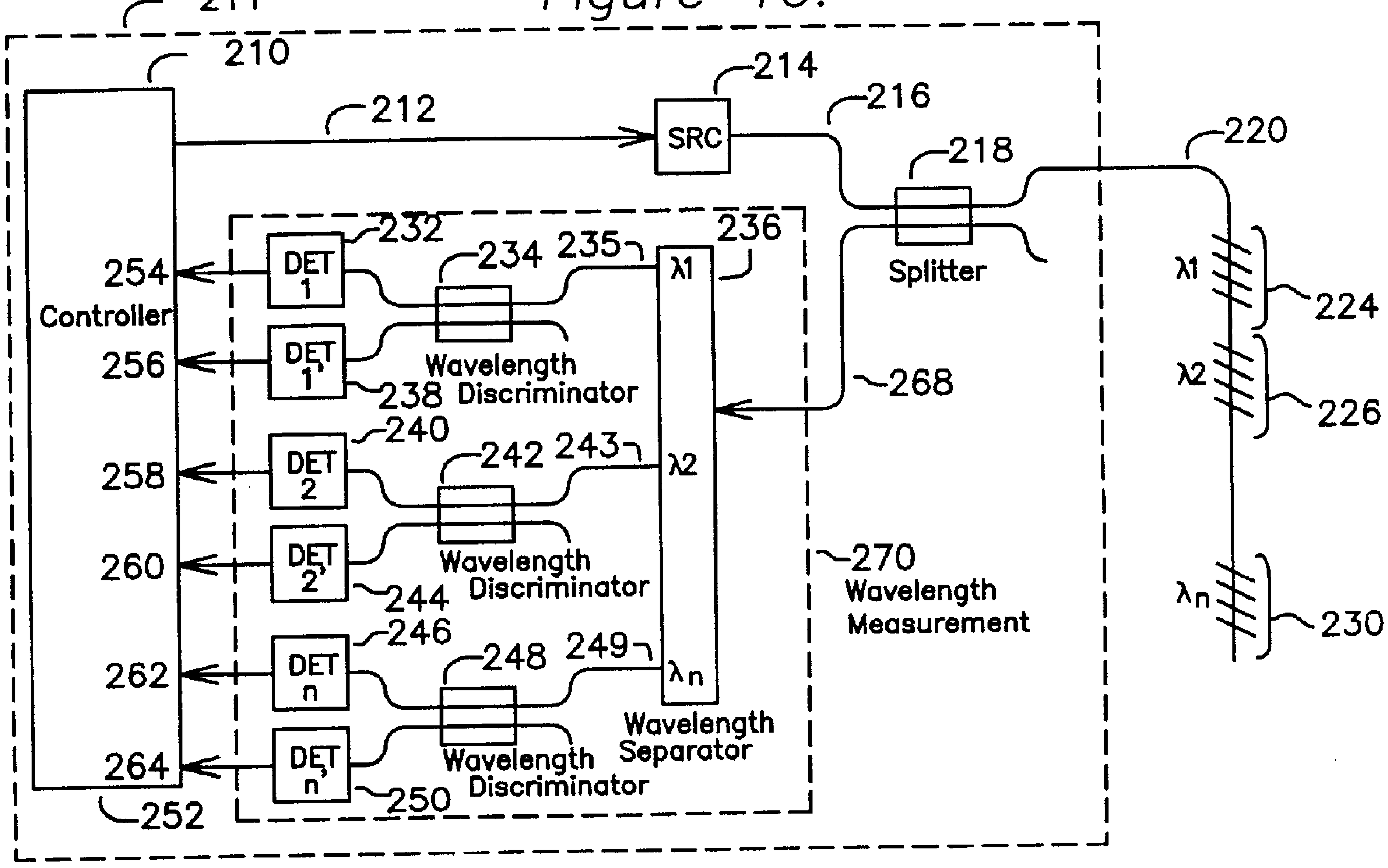



Figure 11:

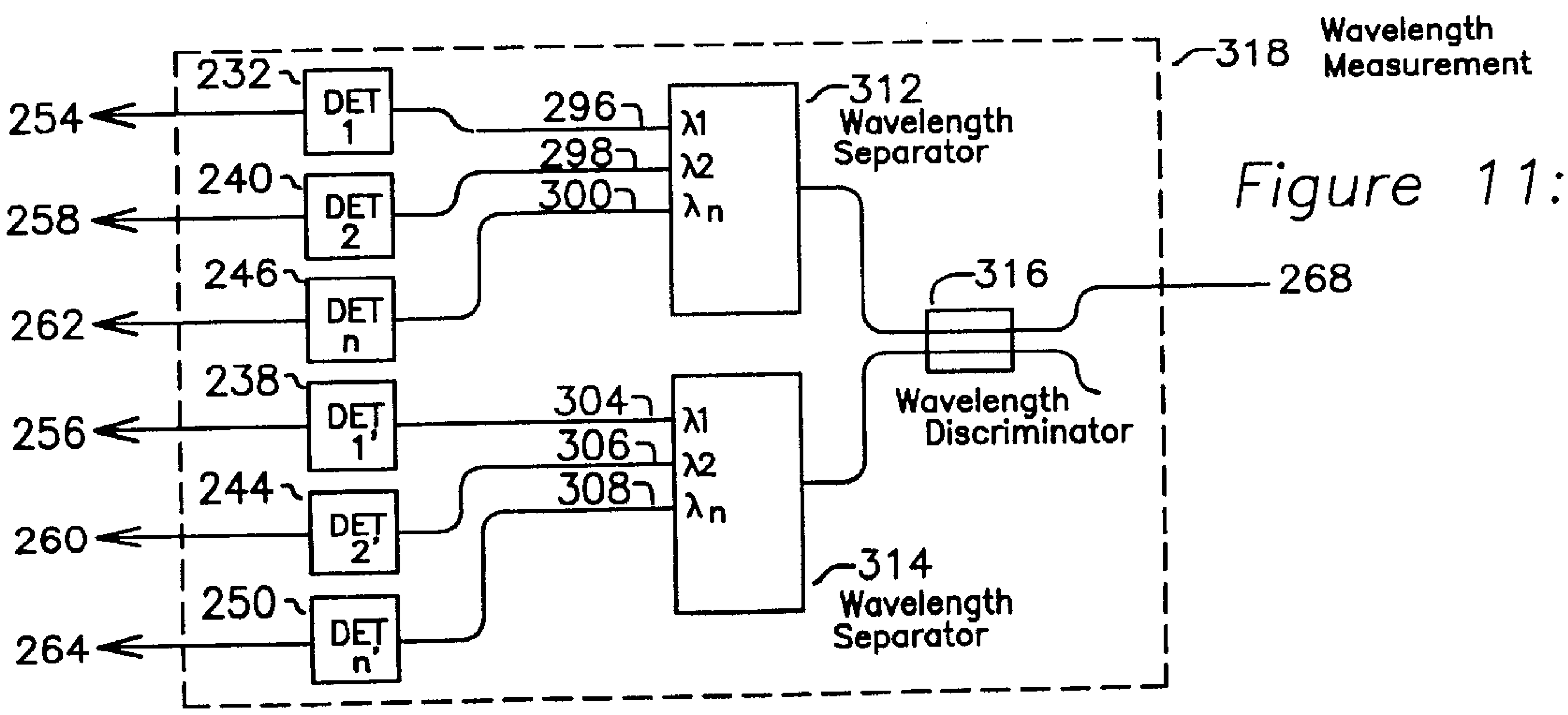


Figure 12:

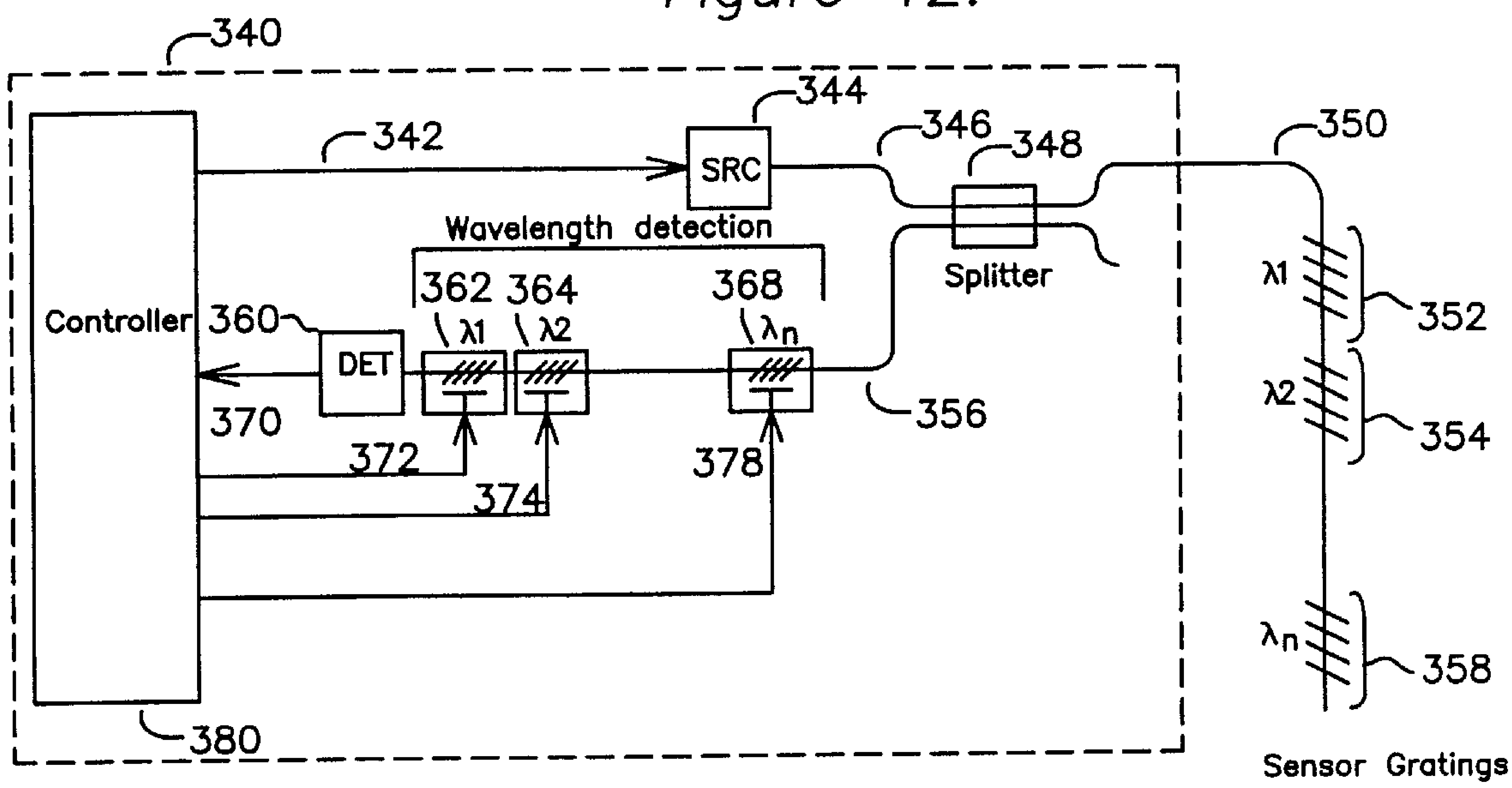



Figure 13:

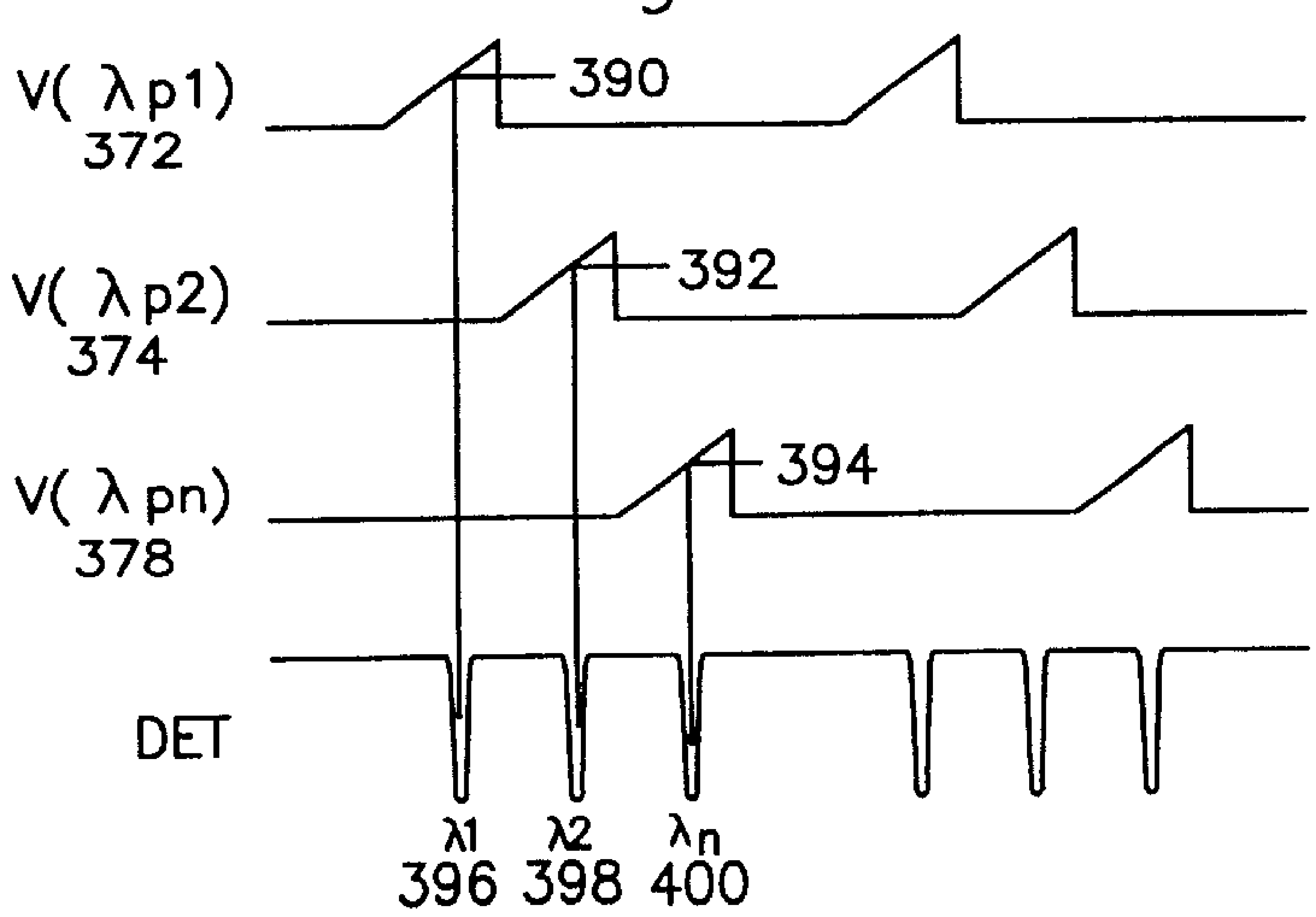


Figure 14:

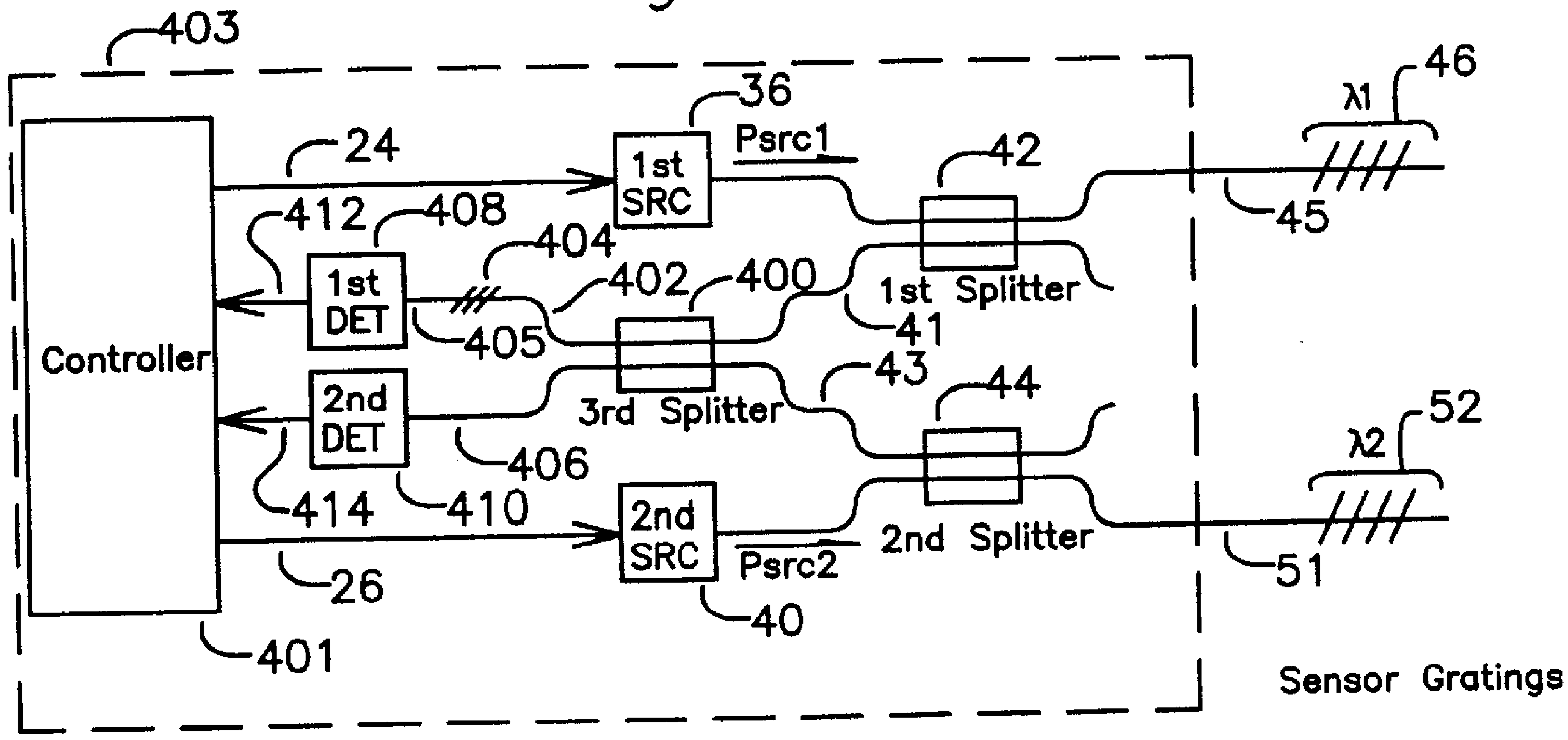



Figure 15:

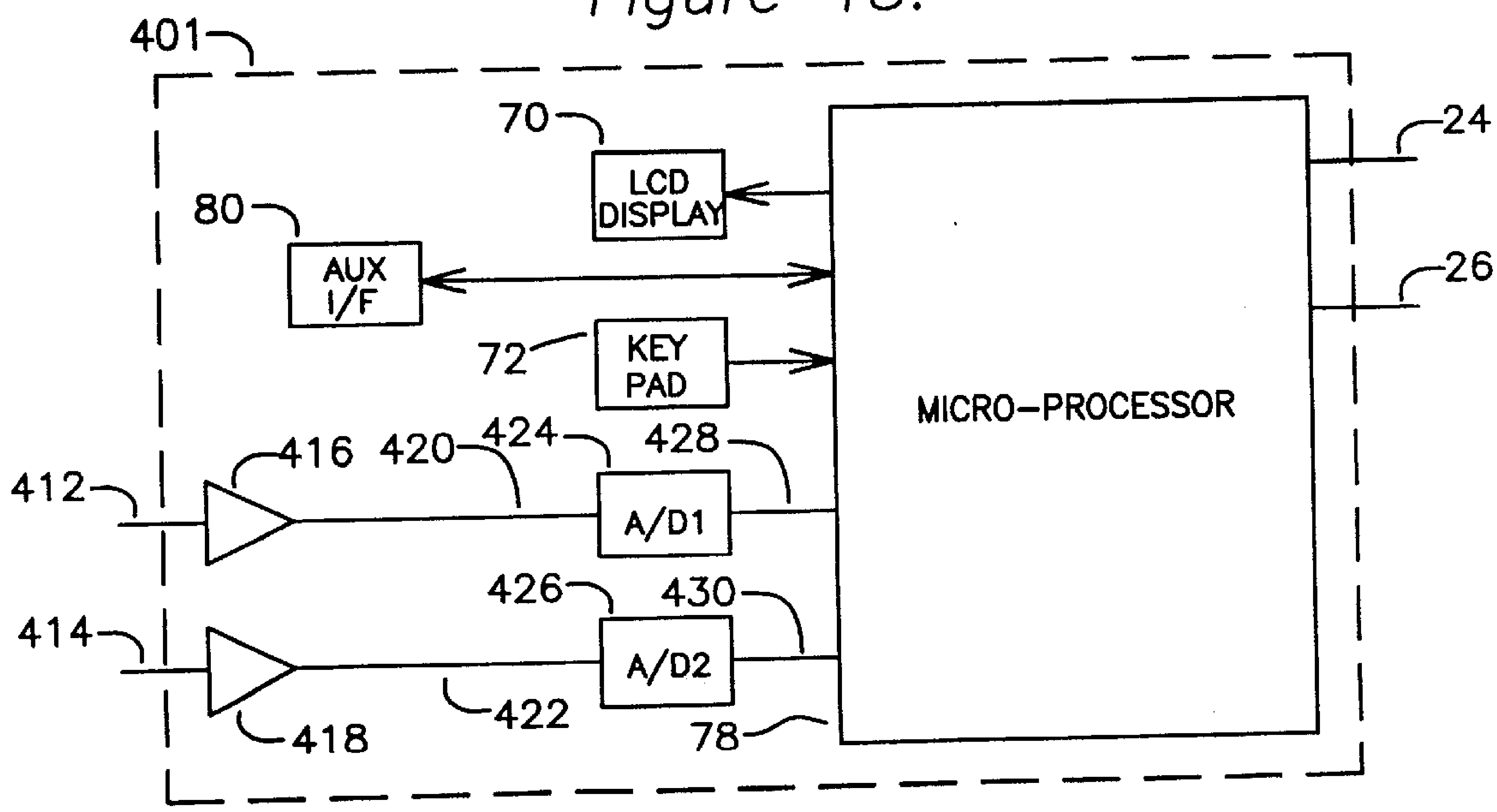


Figure 16:

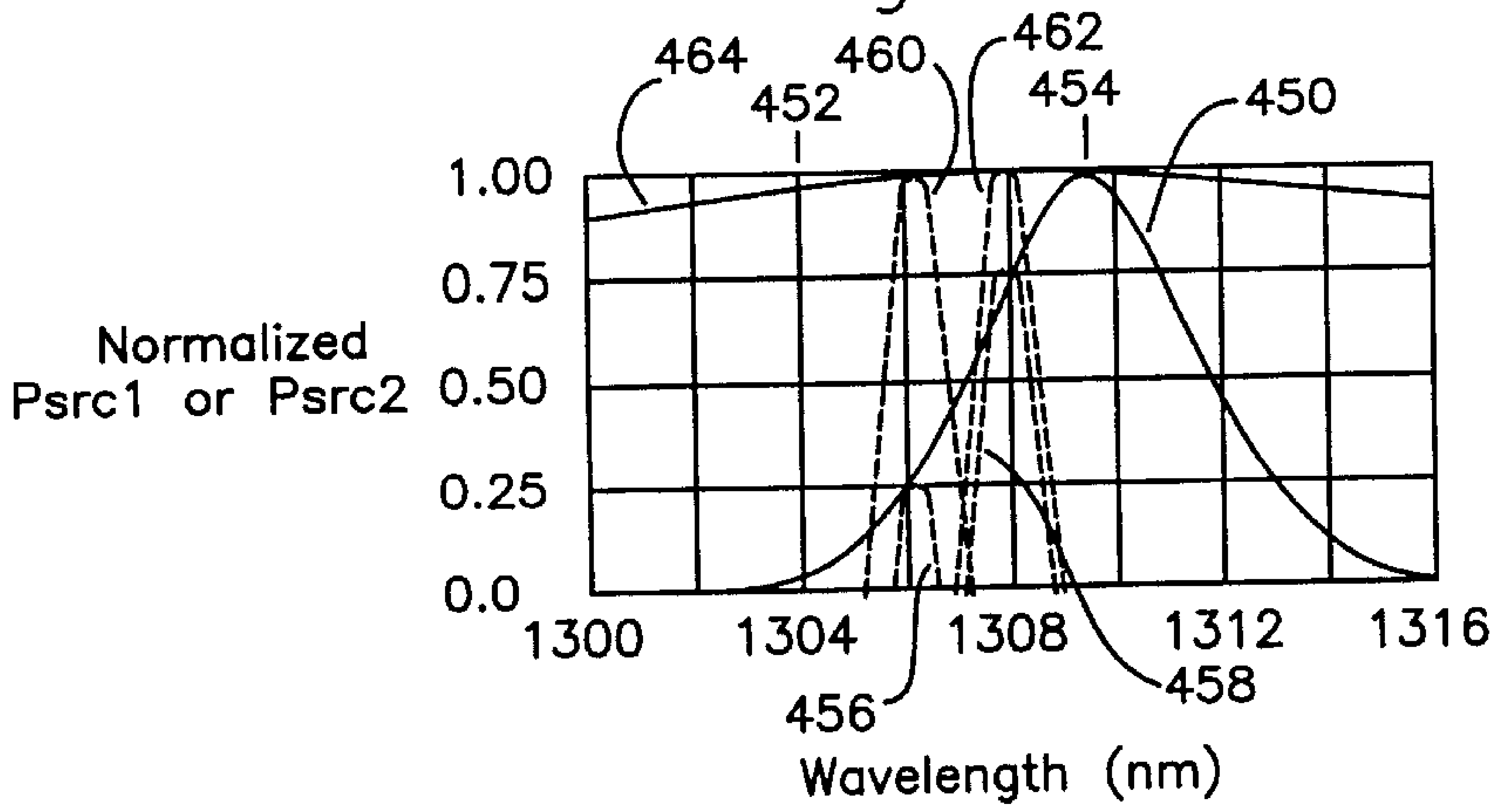



Figure 17:

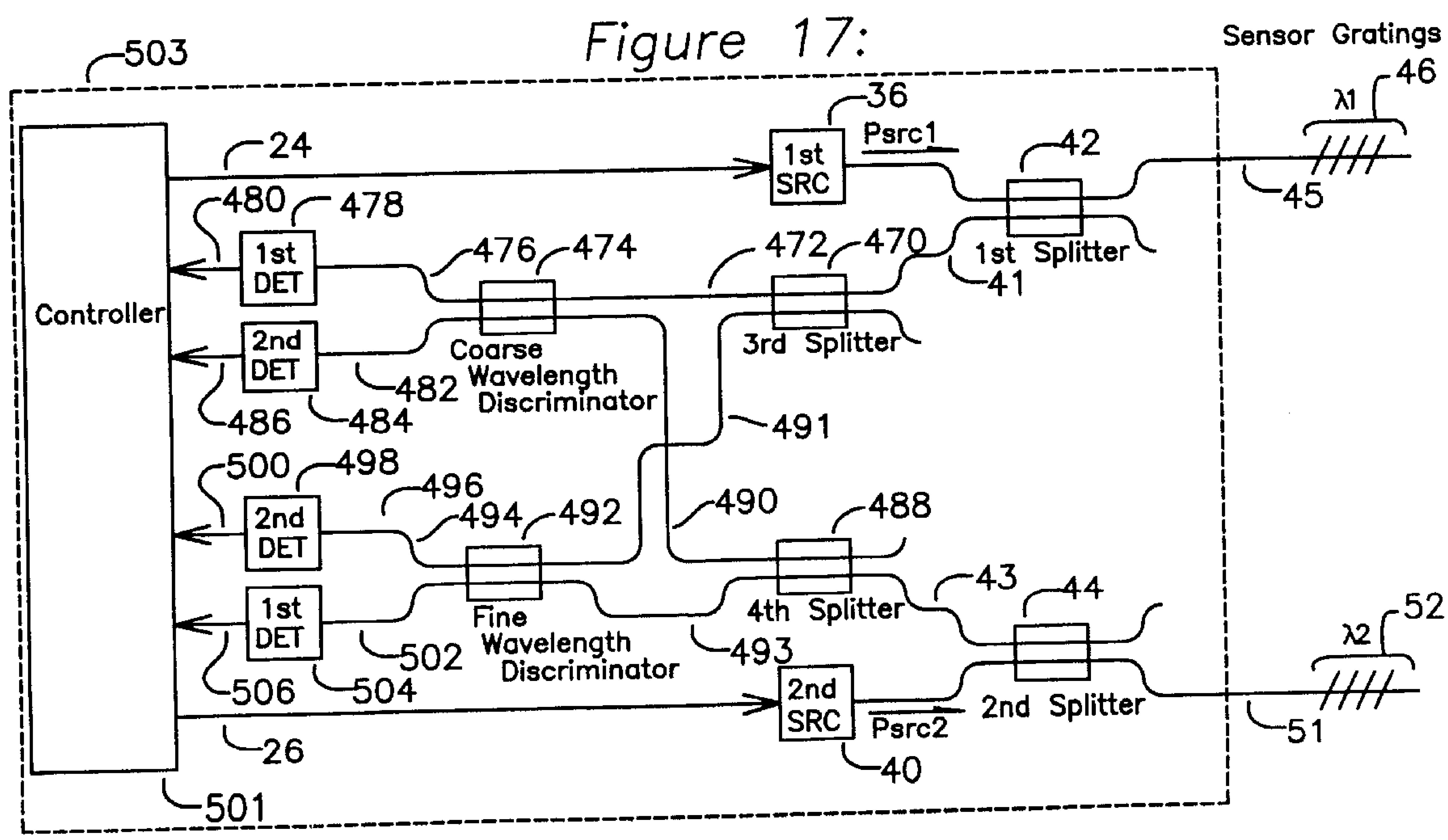
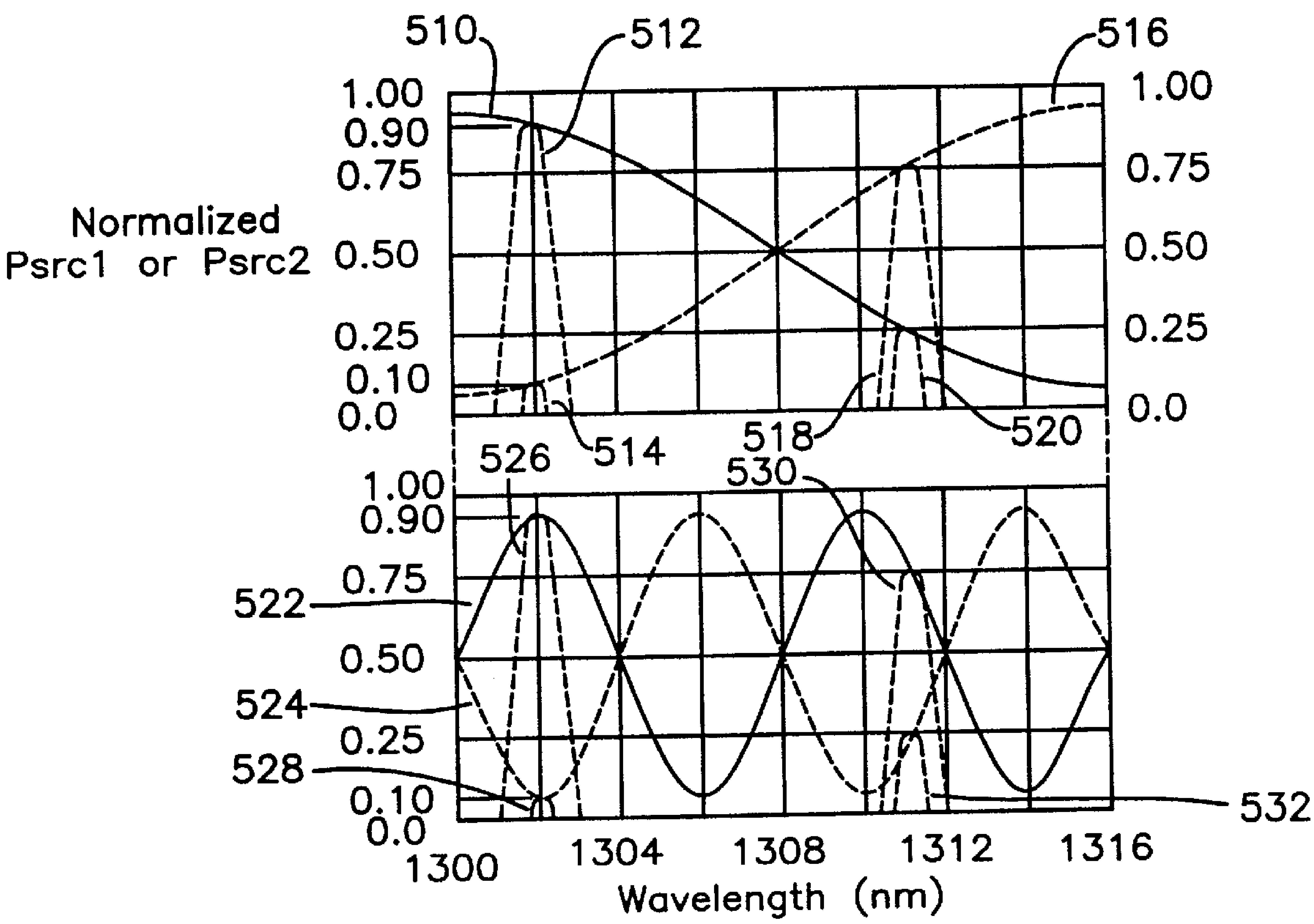


Figure 18:



510
512
516
1.00
0.90
0.75
Normalized
Psrc1 or Psrc2
0.50
0.25
0.10
0.0
514
518
520
526
530
522
524
528
532
1300
1304
1308
1312
1316
Wavelength (nm)

Figure 19a:

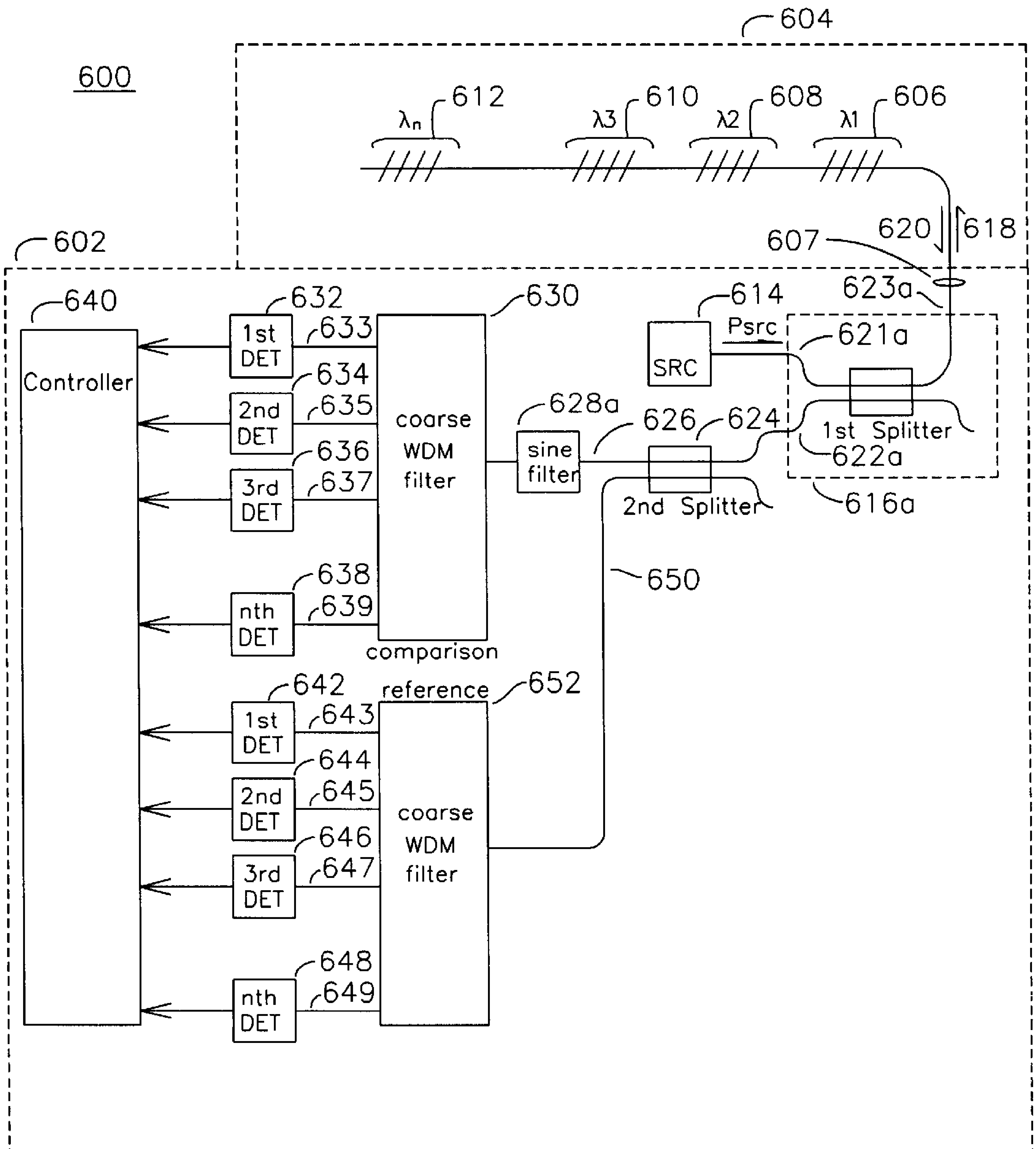

600
604
602
612
610
608
606
$\lambda_n$
λ3
λ2
λ1
607
620
618
623a
614
Psrc
SRC
621a
1st Splitter
622a
616a
624
626
628a
sine filter
2nd Splitter
650
630
coarse WDM filter
comparison
640
Controller
632
1st DET
633
634
2nd DET
635
636
3rd DET
637
638
nth DET
639
642
1st DET
643
644
2nd DET
645
646
3rd DET
647
648
nth DET
649
reference
652
coarse WDM filter

Figure 19b:

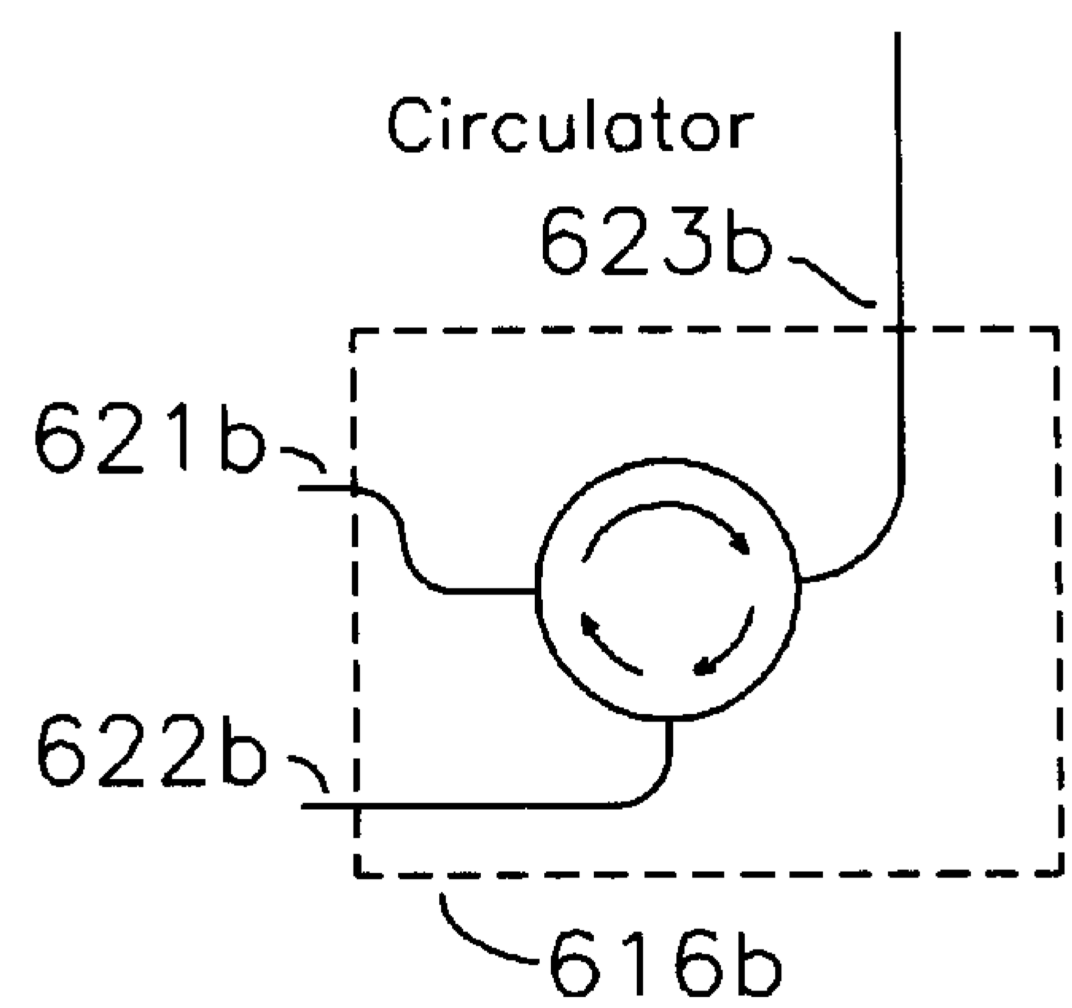



Figure 19c:

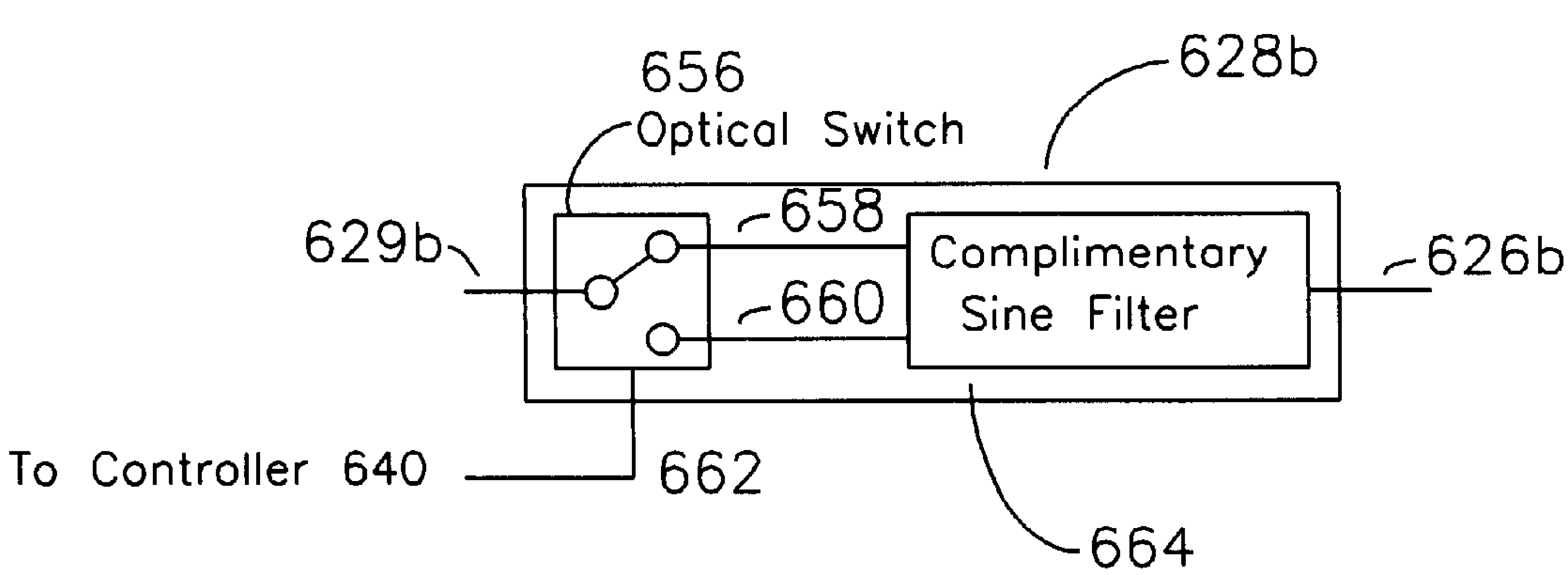


Figure 20a:

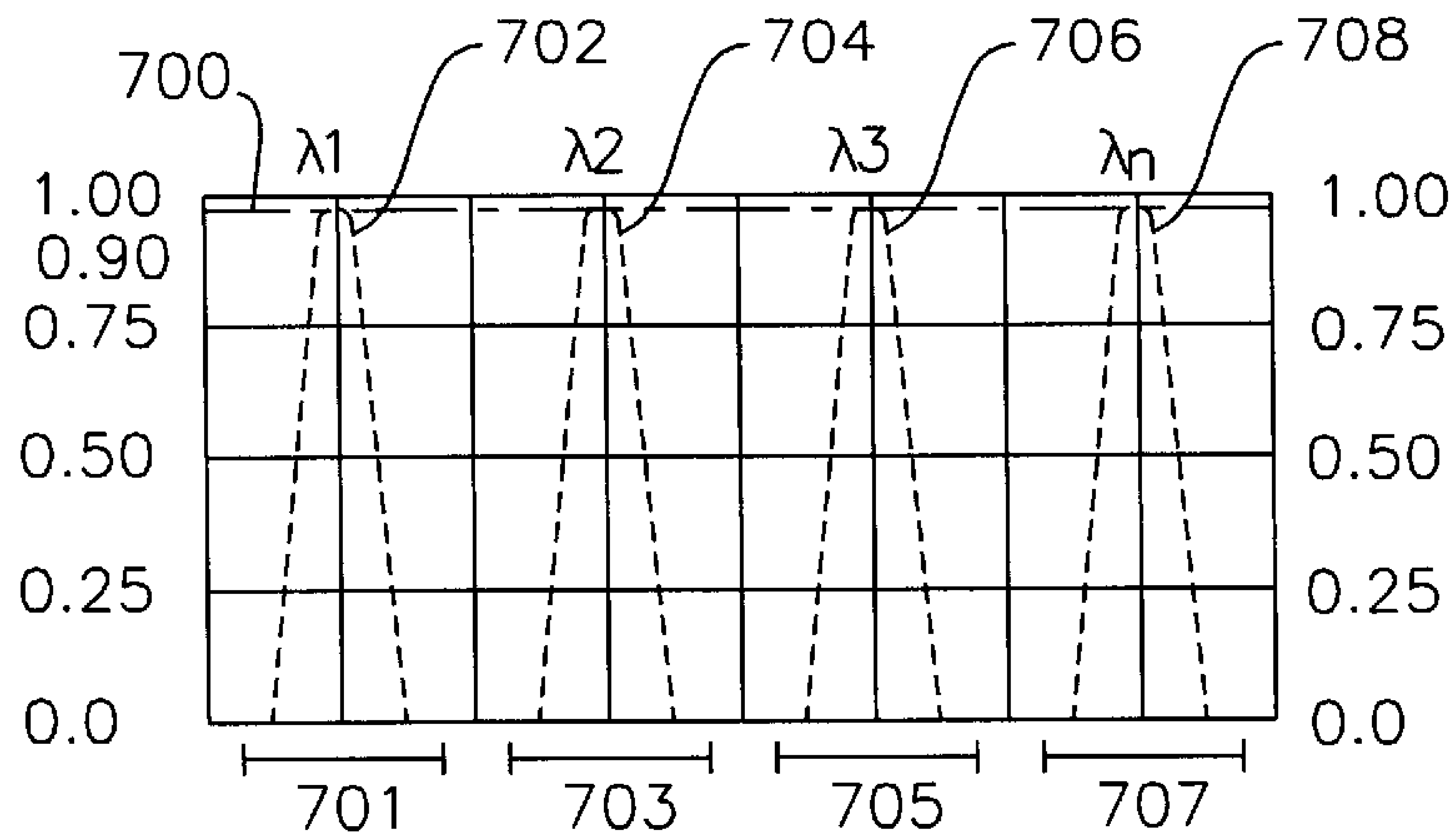



Figure 20b:

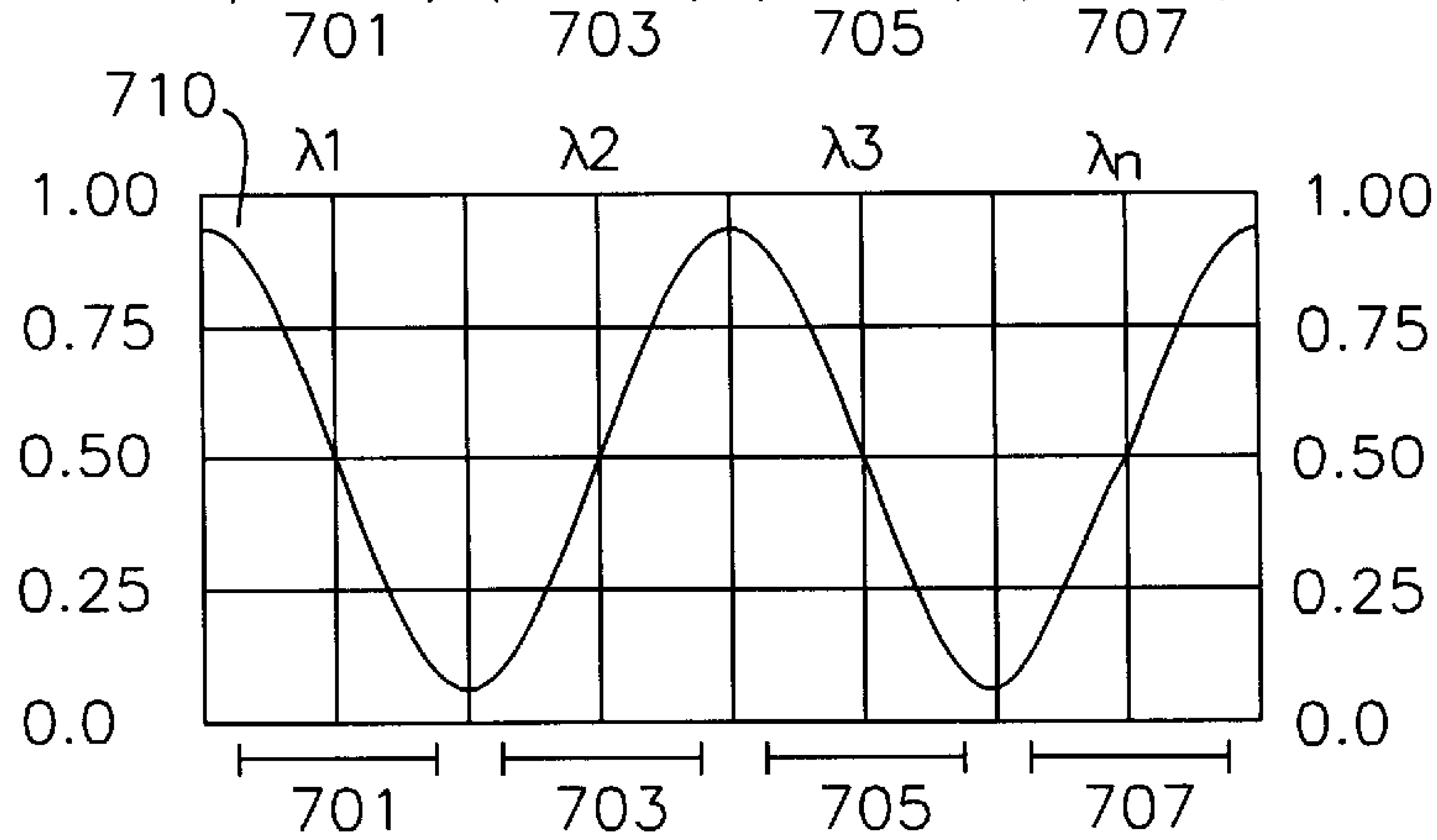



Figure 20c:

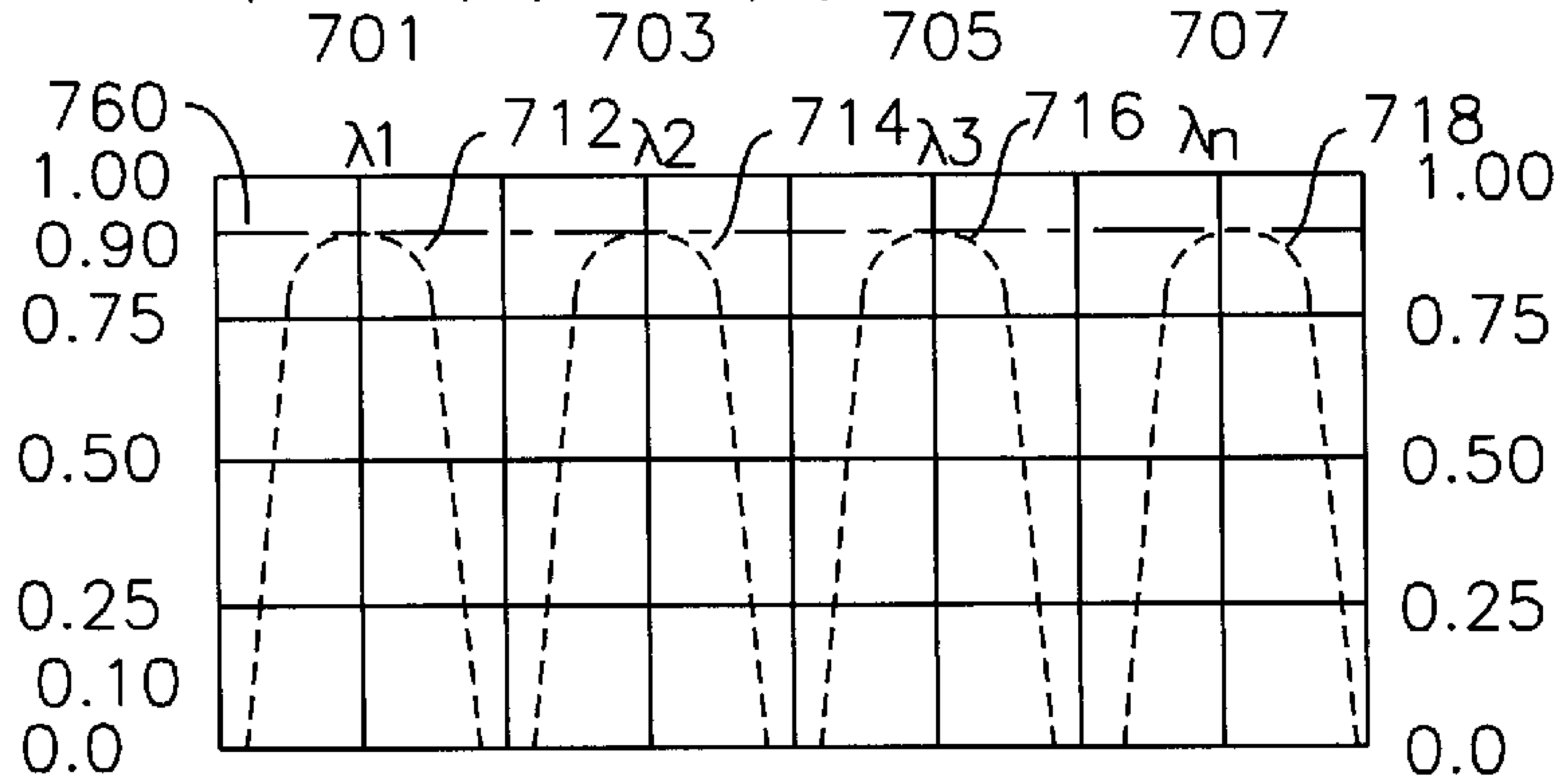



Figure 20d:

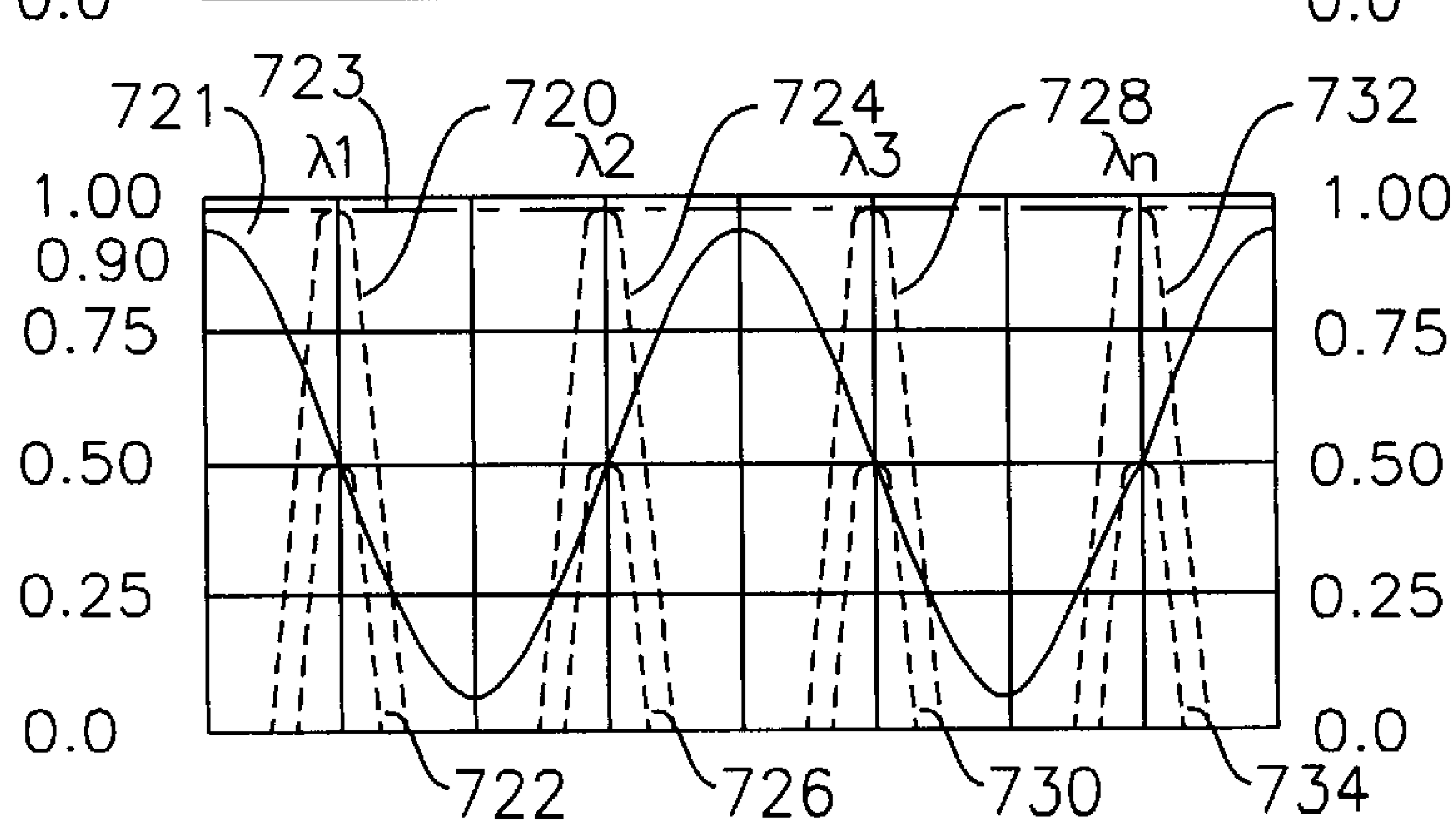


Figure 20e:

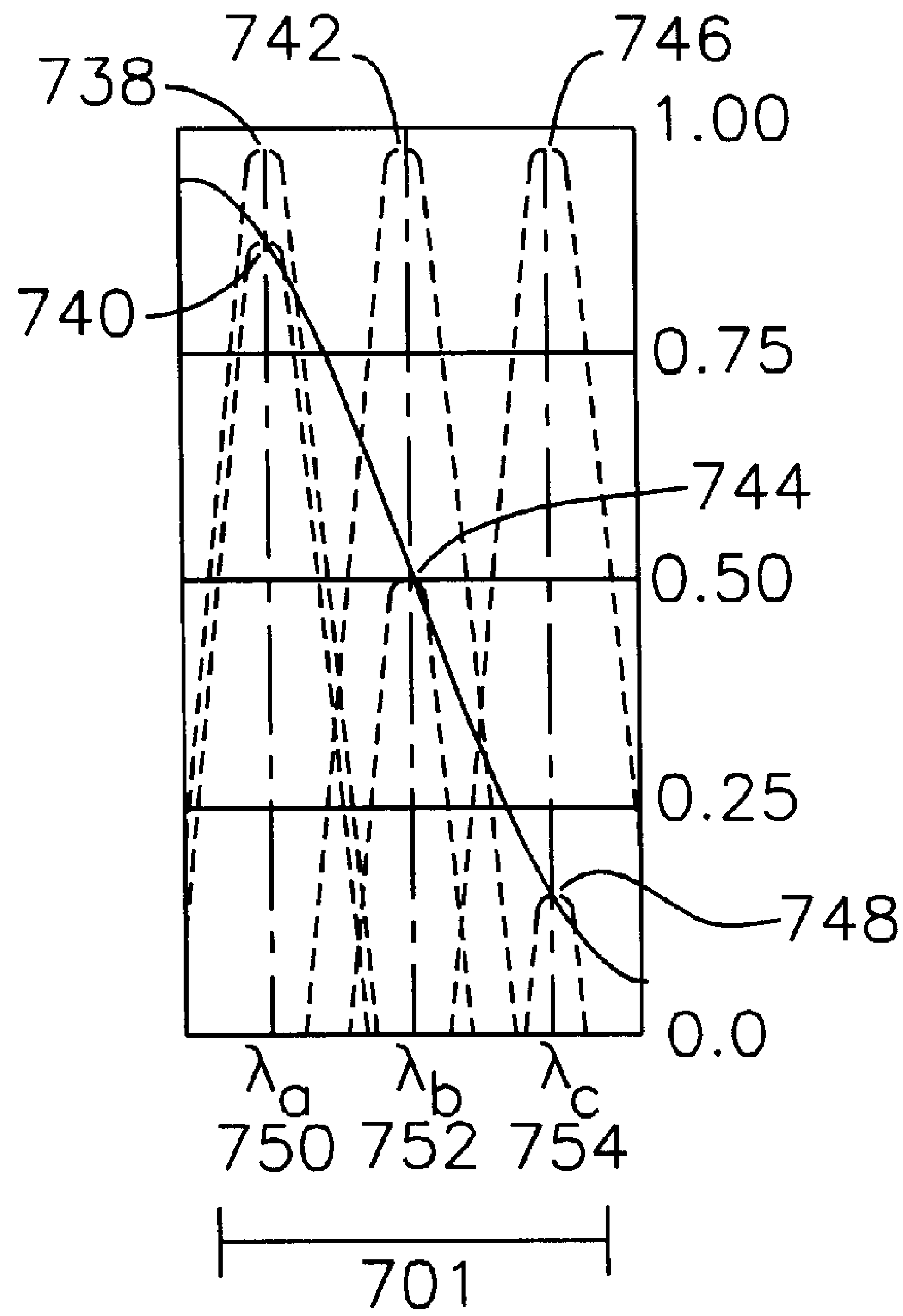
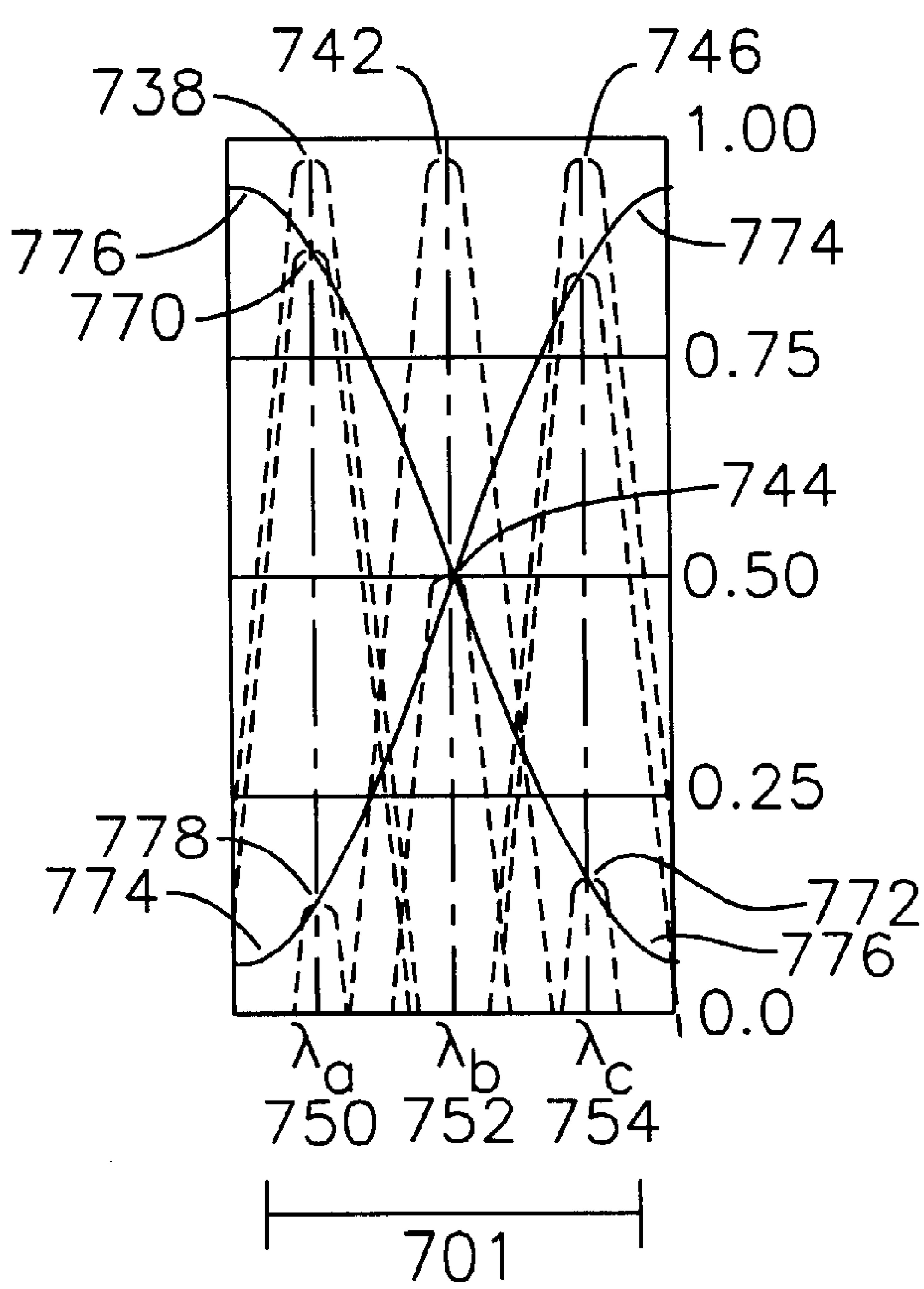



Figure 20f:



# MULTIPLEXABLE FIBER-OPTIC STRAIN SENSOR SYSTEM WITH TEMPERATURE COMPENSATION CAPABILITY

The present invention is a continuation in part application of U.S. patent application Ser. No. 09/286,092 filed Apr. 2, 1999, now U.S. Pat. No. 6,597,822; issued Jul. 22, 2003.

This invention was made with U.S. Government support under grant NAS 1-20579 awarded by the National Aeronautics and Space Administration. The U.S. Government has certain rights in this invention.

## FIELD OF THE INVENTION

The current invention applies to the field of fiber-optic sensors, wherein a dimensional change in a fiber having a Bragg grating is detected using a measurement system comprising broad band sources, optical power splitters, a high-sensitivity wavelength discriminator, optical detectors, and a controller.

## BACKGROUND OF THE INVENTION

There are several modern methods for fabricating optical waveguides for the low-loss containment and delivery of optical waves. One such waveguide is optical fiber which slightly higher index of refraction than the surrounding cladding. Typical values for the core diameter are of order 10 μm for single-mode fiber operating at communications wavelengths of 1300–1550 nm, and 50 μm or 62.5 μm for highly multi-mode fiber. Whether single-mode or multi-mode, the cladding diameter has most commonly an overall diameter of 125 μm, and a plastic jacket diameter is typically 250 μm for standard telecommunications fiber. The glass core is generally doped with germanium to achieve a slightly higher index of refraction than the surrounding cladding by a factor of roughly 1.003. The jacket is generally plastic and is used to protect the core and cladding elements. It also presents an optically discontinuous interface to the cladding thereby preventing coupling modes in the cladding to other adjacent fibers, and usually plays no significant part in the optical behavior of the individual fiber other than the usually rapid attenuation of cladding modes in comparison with bound core modes.

As described in the book by Snyder and Love entitled "Optical Waveguide Theory" published by Chapman and Hall (London, 1983), under the assumptions of longitudinal invariance and small index differences for which the scalar wave equation is applicable, the modal field magnitudes may be written

$$\Psi(r,\phi,z)=\psi(r,\phi)\exp\{i(\beta z-\omega t)\}$$

where

β is the propagation constant

ω is the angular frequency

t is time

z is the axial distance

r,φ is the polar trans-axial position along the fiber.

Single-mode fibers support just one order of bound mode known as the fundamental-mode which we denote as $\psi_{01}$, and which is often referred to in the literature as $LP_{01}$. The transverse field dependence for the fundamental-mode in the vicinity of the core may be approximated by a gaussian function as

$$\psi_{01}(r,\phi)=\exp\{-(r/r_{01})^2\}$$

where $r_{01}$ is the fundamental-mode spot size.



Optical fiber couplers, also known as power splitters, are well known in the art, and generally comprise two fibers as described above having their jackets removed and bonded together with claddings reduced so as to place the fiber cores in close axial proximity such that energy from the core of one fiber couples into the core of the adjacent fiber. One such coupler is a fused coupler, fabricated by placing two fibers in close proximity, and heating and drawing them. The finished fused coupler has the two cores in close proximity, enabling the coupling of wave energy from one fiber to the other. A further subclass of fused coupler involves a substantially longer coupling length, and is known as a wavelength discriminator. The characteristics of a wavelength discriminator include wavelength-selective coupling from an input port to a first output port, as well as a second output port. As the wavelength is changed over the operating range of the wavelength discriminator, more energy is coupled into the first output port, and less is coupled into the second output port. The operation of a wavelength discriminator is described in "All-fibre grating strain-sensor demodulation technique using a wavelength division coupler" by Davis and Kersey in Electronics Letters, Jan. 6, 1994, Vol. 30 No. 1.

Fiber optic filters are well known in the art, and may be constructed using a combination of optical fiber and gratings. Using fiber of the previously described type, there are several techniques for creating fiber optic gratings. The earliest type of fiber grating-based filters involved gratings external to the fiber core, which were placed in the vicinity of the cladding as described in the publication "A single mode fiber evanescent grating reflector" by Sorin and Shaw in the Journal of Lightwave Technology LT-3:1041–1045 (1985), and in the U.S. patents by Sorin U.S. Pat. No. 4,986,624, Schmadel U.S. Pat. No. 4,268,116, and Ishikawa U.S. Pat. No. 4,622,663. All of these disclose periodic gratings which operate in the evanescent cladding area proximal to the core of the fiber, yet maintain a separation from the core. A second class of filters involve internal gratings fabricated within the optical fiber itself. One technique involves the creation of an in-fiber grating through the introduction of modulations of core refractive index, wherein these modulations are placed along periodic spatial intervals for the duration of the filter. In-core fiber gratings were discovered by Hill et al and published as "Photosensitivity in optical fiber waveguides: Application to reflected filter fabrication" in Applied Physics Letters 32:647–649 (1978). These gratings were written internally by interfering two counter propagating electromagnetic waves within the fiber core, one of which was produced from reflection of the first from the fiber end face. However, in-core gratings remained a curiosity until the work of Meltz et al in the late 1980s, who showed how to write them externally by the split-interferometer method involving side-illumination of the fiber core by two interfering beams produced by a laser as described in the publication "Formation of Bragg gratings in optical fibers by a transverse holographic method" in Optics Letters 14:823–825 (1989). U.S. patents Digiovanni U.S. Pat. No. 5,237,576 and Glenn U.S. Pat. No. 5,048,913, also disclose Bragg gratings, a class of grating for which the grating structure comprises a periodic modulation of the index of refraction over the extent of the grating. Short-period gratings reflect the filtered wavelength into a counter-propagating mode, and, for silica based optical fibers, have refractive index modulations with periodicity on the order of a third of the wavelength being filtered. Long-period gratings have this modulation period much longer than the filtered wavelength, and convert the energy of one mode into another mode propagating in the same direction, i.e., a co-propagating mode, as described in the publication "Efficient mode conversion in telecommunication fibre using externally written gratings" by Hill et al in Electronics Letters 26:1270–1272 (1990). The grating comprises a periodic variation in the index of refraction in the principal axis of the core of the fiber, such variation comprising a modulation on the order of 0.1% of the refractive index of the core, and having a period associated with either short or long-period gratings, as will be described later.

The use of fiber-optics in temperature measurement is disclosed in U.S. Pat. No. 5,015,943 by Mako et al. A laser source is beam split into two fibers, one of which is a sensing fiber exposed to an elevated temperature, and one of which is a reference fiber in an ambient environment. The optical energy from the two fibers is summed together, and an interference pattern results. As the temperature changes, the physical length of the sensing fiber optic cable changes, which causes the interference pattern to modulate. Each modulation cycle represents one wavelength change in length. Counting these interference patterns over time enables the measurement of temperature change.

## SUMMARY OF THE INVENTION

The present invention is directed to an apparatus for the measurement of sensor grating pitch, wherein the change in grating pitch can originate from a strain applied to the sensor grating, or it may originate from a temperature change wherein the sensor grating expands or contracts due to the coefficient of thermal expansion of the optical fiber enclosing the sensor grating. A pair of fibers, each having a sensor grating, is illuminated by a pair of broadband sources coupled through a pair of optical power splitters, and this sensor grating reflects wave energy over a narrow optical bandwidth. Reflected wave energy from the narrow-band sensor grating is passed through a wavelength discriminator, comprising a long-drawn optical coupler. A normalized power ratio comprises the difference in first and second detector power levels divided by the sum of the first and second power level. This intensity ratio is compared to the wavelength discriminator characteristic stored in a controller to look up the wavelength from a normalized power ratio value, and hence the pitch of the sensor grating. As the characteristic of the wavelength discriminator is essentially temperature invariant, this very accurately yields the sensor grating pitch. Comparing this reflected wavelength to the known wavelength of the grating indicates a change in wavelength brought about by either a temperature change or by the presence of a strain. In the case where a second sensor is also monitored, one sensor may be used as a reference to monitor the temperature of the second sensor, which is used to measure applied strain. In this manner, the temperature effect of the strain gauge may be cancelled by using the measured result of the reference sensor. Commutating the two sources in separate non-overlapping intervals enables the independent measurement of temperature, or strain, or any combination of the two.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1***a* is a prior art grating.

FIGS. **1***b, c, d* show the spectral behavior of the prior art grating of FIG. **1***a*.



FIG. **1***e* is a prior art coupler/wavelength discriminator

FIG. **1***f* is a section view of the fused area of FIG. **1***e*.

FIG. **2** is a block diagram of the fiber optic sensor system.

FIG. **3** is a block diagram of the controller of FIG. **2**.

FIG. **4** is a wavelength discriminator.

FIG. **5** is a graph of the response of a wavelength discriminator including reflected grating power applied to this wavelength discriminator.

FIG. **6** is a graph of the output function of the wavelength discriminator normalized power ratio **(P1−P2)/(P1+P2)**.

FIG. **7** is the dynamic state of various internal nodes of the fiber optic sensor system during operation.

FIG. **8** is a three-wavelength, temperature/strain sensor.

FIG. **9** shows the wavelength detection properties of FIG. **8**.

FIG. **10** is a multi-wavelength strain/temperature measurement system.

FIG. **11** is an alternate wavelength detector for FIG. **10**.

FIG. **12** is a multi-wavelength strain/temperature measurement system using tunable gratings.

FIG. **13** shows the voltage waveforms for FIG. **12**.

FIG. **14** shows a temperature/strain measurement system having an alternate wavelength discriminator comprising a broadband grating and a splitter.

FIG. **15** shows the block diagram of the measurement controller of FIG. **14**.

FIG. **16** shows the input to the first and second detectors versus wavelength for the measurement system of FIG. **14**.

FIG. **17** shows a temperature/strain measurement system using a wavelength discriminator comprising a coarse wavelength discriminator and a fine wavelength discriminator.

FIG. **18** shows the characteristic transfer function for the fine wavelength discriminator and the coarse wavelength discriminator of FIG. **17**.

FIG **19***a* shows the block diagram for a temperature and strain measurement system.

FIG. **19***b* show an alternate 1st splitter for the system of FIG. **19***a*.

FIG. **19***c* shows an alternate sine filter for the system of FIG. **19***a*.

FIGS. **20***a*, **20***b*, **20***c*, **20***d*, **20***e*, and **20***f* show the spectral graphs of the measurement system of FIG. **19**.

## DETAILED DESCRIPTION OF THE INVENTION

FIG. **1***a* shows a prior art internal grating filter, comprising an optical fiber having a core **1**, a cladding **2**, and a grating **3** fabricated within the extent of the core **1**. The grating **3** comprises a modulation of the index of refraction of core **1** having a regular pitch **4**, where the grating **3** is used to create short-period grating behavior. For reflection of waves through the grating at wavelength $\lambda_b$, the short-period grating function is as follows:

$$\Lambda_b=\lambda_b/2n$$

where

- $\Lambda_b$=pitch of the desired Bragg grating,
- $\lambda_b$=conversion wavelength: For short period gratings, $\lambda_b$ is the wavelength for which incident fundamental mode wave energy is converted to counter-propagating (traveling in the opposite direction) wave energy.
- n=effective index of refraction of the fiber, which is dependant on the mode of the propagated wave.

Examining now the transfer curves for a short-period grating **3**, FIG. **1***b* shows the input source spectrum **7** applied to port **5**, and FIG. **1***c* shows the reflected spectrum **8** and grating peak **9** reflected back to port **5**. FIG. **1***d* shows the remaining optical energy continuing to port **6**. Filter notch **11** represents wave energy reflected by the short period Bragg grating back to the input port **5**, and is represented as spectrum **8** having peak **9** corresponding to the Bragg wavelength. The use of reflected wave energy at peak **9** is generally not available without the use of an optical coupler or some other device sensitive to the propagating direction of this wave.

FIG. **1***e* shows a prior art optical coupler. First fiber having a core **12** and cladding **13** is placed in proximity with a second fiber having a core **15** and a cladding **14**. Together, these fibers are heated and drawn to fuse the two fibers into one having a coupling length **16**. FIG. **1***f* shows a section view of this fused middle section. Coupling length **16** and separation **17** determine the coupling characteristics of the coupler. If the coupling length **16** is short, a broadband coupler having a coupling coefficient related to separation **17** is formed. This is the typical construction for power splitter configurations. If the length **16** is many wavelengths long, a narrowband coupler is formed, also known as a wavelength discriminator. The characteristics of a wavelength discriminator are similar to those of a coupler, with an additional wavelength dependence, as shown in FIG. **5**, which is described later.

FIG. **2** shows the present fiber-optic sensor. Measurement system **20** is coupled to fibers **45** and **51**. Each of fibers **45** and **51** has a Bragg grating **46** and **52** respectively. Measurement system **20** further comprises a controller **22** having a first source enable output **24** coupled to first source **36**, which may be any source of optical energy having a spectrum which includes the wavelength of the grating **46** on fiber **45**. A broadband light-emitting diode (LED) would provide an inexpensive broadband source. Similarly, second source enable output **26** is coupled to second source **40**, which has the same requirement of including in its output spectrum the wavelengths of the grating **52** of fiber **51**. Broadband sources **36** and **40** respectively couple energy through standard power splitters **42** and **44**, which provide optical energy to gratings **46** and **52** respectively. The gratings **46** and **52** may be internal Bragg gratings or external short period gratings. The short-period grating has the property of reflecting optical energy at the grating wavelength back to couplers **42** and **44**, where it is split into optical energy provided to cables **41** and **43** to wavelength discriminator **38**, the operation of which will be discussed later in FIG. **4**. Output wave energy from wavelength discriminator **38** is separated into a first output on fiber **31** travelling to first detector **30**, which provides a voltage **28** proportional to the input optical level delivered on fiber **31**. Similarly, optical wave energy from the second output **33** of wavelength discriminator **38** is delivered to the second detector **34**, which produces a voltage **32** to controller **22** proportional to the input optical level delivered on fiber **33**.

FIG. **3** describes in detail the controller **22** of FIG. **2**. Controller **22** further comprises a microprocessor **78** which produces first source enable output **24** and second source enable output **26**. In addition, first detector input **28** and second detector input **32** are processed by buffer amplifiers **62** and **64** respectively, which isolate the detector element from the following electronics, and produce respectively outputs **82** and **84**. These are processed by a difference amplifier **66** to produce a difference output at **86**, which is converted from an analog signal to a digital signal by A/D converter **74**, delivering a digital representation **90** of this signal to microprocessor **78**. Amplifier **68** produces a detector sum output **88**, which is similarly converted to a digital signal **92** by A/D converter **76**, which is also input to microprocessor **78**. A keypad **72** for input and a display **70** are also coupled to the microprocessor **78**, as is an auxiliary interface **80**. Microprocessor **78** may be chosen from several available units, including the PIC16C71 from Micro-Chip, Inc. of Chandler, Ariz., which has the A/D converters **74** and **76** incorporated internally. As is clear to one skilled in the art, many microprocessor choices are available for **78**, including devices with internal or external ROM, RAM, A/D converters, and the like, of which many candidates from the Micro-Chip PIC-16 family would be suitable. While a particular microprocessor is shown for illustrative purposes, it is clear to one skilled in the art that other units could be substituted for these devices without changing the operation of the sensor. The principal requirements of microprocessor **78** are the ability to control the first and second sources, and to process the values provided by the first and second detectors in a manner which determines the wavelength of the sensor grating.

FIG. **4** shows the wavelength discriminator **38**. The wavelength discriminator has a first splitter input port **41**, a second splitter input port **43**, a first detector output port **31**, and a second detector output port **33**. FIG. **5** shows the normalized output of wavelength discriminator **38** for the case where a swept-wavelength input is applied to first splitter input **41**, and no input is provided to second splitter input **43**. Curve **100** shows the output level of first detector output **31**, while curve **104** shows the output level of second detector output **33**. As can be seen from the graph, as the wavelength is varied from 1300 nm to 1316 nm, the first detector and second detector outputs vary in a complimentary manner, such that the sum of the first detector output and second detector output is nearly constant. The wavelength discriminator is a symmetric device, so if no optical signal were applied to first input **41** and a swept wavelength optical signal were applied to second input **43**, curve **100** would show the level of second output port **33**, while curve **104** would show the level of first output port **31**.

FIG. **6** shows a plot for normalized power ratio derived from first output curve **100** and second output curve **104**. If these two complimentary curves **100** and **104** are plotted as **(P1−P2)/(P1+P2)**, then the plot of FIG. **6** results, and we may now determine wavelength over monotonic regions such as from 1304 nm to 1312 nm by simply looking up the wavelength given the **(P1−P2)/(P1+P2)** normalized power ratio. Curve **114** represents the response to first source **36**, and curve **112** represents the response to second source **40**. The advantage of performing this lookup in this ratiometric manner of FIG. **6** as opposed to the absolute output level on the curve **100** of FIG. **5** is that variations in source power are normalized out of the result. Specifically, changes in the output power of sources **36** and **40** would modulate the values shown in plots **100** and **104** of FIG. **5**, but not the normalized power ratio shown in the plot of FIG. **6**.

Further examining the operation of the measurement system of FIG. **2**, the first measurement is performed with only first source **36** enabled. Optical energy travels through first coupler **42** to fiber **45**, and to grating **46**. Optical energy at the wavelength $\lambda_1$ of grating **46** is reflected through fiber **45** back to first coupler **42**, through fiber **41**, where it is presented to wavelength discriminator **38**. No input is present on fiber **43** because second source **40** is not enabled. Optical energy from grating **46** is reflected, for example, at $\lambda_1$=1309 nm, as shown in curve **102** of FIG. **5**, and 0.4 volts is generated at **28** by first detector **30**. The second output **33** of wavelength discriminator **38** is applied to the second detector **34**, producing 0.6 volts at **32** as shown in curve **103** of FIG. **5**. By now finding the normalized power ratio of (0.4–0.6)/(0.4+0.6)=–20, it can be seen that this corresponds to 1309 nm wavelength on curve **114** at point **109** in FIG. **6**.

An entirely separate measurement can be made by disabling first source **36** and enabling second source **40**. In this case, optical energy would leave second splitter **44** through fiber **51** to grating **52**. Optical energy at wavelength $\lambda_2$ **52** would be returned to second splitter **44** through fiber-optic cable **51**, leave second splitter **44** through fiber-optic cable **43**, entering wavelength discriminator **38**. Analogous to the earlier described processing, first source **36** would be disabled, hence no optical energy would be present in fiber **41**. In the case of wave energy input to fiber **43** instead of fiber **41**, the output characteristic of FIG. **5** would be reversed such that curve **100** would be the output energy on fiber **33**, and curve **104** would represent the output energy of fiber **31**. If the grating **52** were reflecting at $\lambda_2$=1306 nm, then second detector **34** would produce 0.75 volts as shown in curve **108** of FIG. **5**. First detector **30** would produce 0.25 volts as shown in curve **106** of FIG. **5**. The normalized power ratio of FIG. **6** would be (0.25–0.75)/(0.25+0.75)=–0.5, corresponding to 1306 nm on curve **112** of FIG. **6** at point **107**.

FIG. **7** shows the sensor measurement system operating in the earlier-described case where the wavelength of first sensor **46** is $\lambda_1$=1309 nm and the wavelength of second sensor **52** is $\lambda_2$=1306 nm. First, the detector offsets are determined by turning both first source **36** and second source **34** off. This produces the detector offset values OS1 and OS2, which will be necessary to subtract from the power difference and power sum before calculation of the normalized power ratio (P1–P2)/(P1+P2). Thereafter, first source **36** and second source **40** are alternately enabled as shown in FIG. **7**. First detector **30** and second detector **34** produce the P1 and P2 values shown, and the difference, sum, and the normalized power ratio value of difference/sum are computed as shown, wherein the power difference (P1–P2) and the sum (P1+P2) represent power quantities after removal of offsets OS1 and OS2, which thereafter form the normalized power ratio (P1–P2)/(P1+P2). If the plot of FIG. **6** normalized power ratio were kept in the memory of the microprocessor, either as a series of interpolated points, or as a power series wherein only the coefficients **f0**, **f1**, **f2**, **f3** . . . fn of a polynomial are stored, and the power

$$\lambda(P1, P2) = f_0 + f_1\left[\frac{P1 - P2}{P1 + P2}\right] + f_2\left[\frac{P1 - P2}{P1 + P2}\right]^2 + f_3\left[\frac{P1 - P2}{P1 + P2}\right]^3 + \ldots + f_n\left[\frac{P1 - P2}{P1 + P2}\right]^n$$

series is of the form

where

λ(P1,P2)=wavelength as a function of detector power ratio (P1–P2)/(P1+P2).

It would be possible to convert the given normalized power ratio(P1–P2)/(P1+P2) back to a wavelength $\lambda_1$=1309 nm for the first sensor, and $\lambda_2$=1306 nm for the second sensor. This determination could be done using either a look-up table derived from the normalized power ratio, or by storing the coefficients of a power series based on the normalized power ratio, and thereafter calculating for wavelength based on this power series.

If the sensors were operating either as temperature sensors or strain sensors, the applied strain or temperature could be computed from the following relationship:

$$\Delta\lambda = \alpha 1 \Delta T + \alpha 2 \Delta S$$

where

Δλ=change in sensor wavelength

α1=coefficient of thermal change for sensor

ΔT=change in sensor temperature

α2=coefficient of strain change for sensor

ΔS=change in sensor strain

In this equation, the change in sensor wavelength is expressed as the sum of a temperature related change and a strain related change. The coefficients α1 and α1 would be stored in the controller along with initial condition values to solve for total strain and total temperature. In this manner, any combinations of strain and temperature could be determined given a change in sensor wavelength and the wavelength discriminator characteristic curve, and first and second detector inputs.

FIG. **8** shows a strain/temperature measurement system having a 3-way wavelength discriminator **162**. This system is analogous to the system described in FIG. **2**, however, for an n-way wavelength discriminator, the output port associated with the excited port has the response shown in plot **186**, while the remaining ports have the characteristic shown in plot **188**. For example, in the case of FIG. **8**, first source **134** sends broadband excitation through first splitter **136**, and wave energy at the example grating wavelength $\lambda_1$=1300 nm is reflected through splitter **136** to wavelength discriminator port **167**. For this case, the output at port **168** has the characteristic shown in plot **186**, while the second output **174** and third output **180** have the responses shown by curve **188**. For $\lambda_1$=1300 nm, the response of the first detector is shown as point **192**, while the second the third detectors have the response shown by point **194**. As before, a normalized plot of the response of curves **186** and **188** is shown in plot **190**. For the case of an n-way wavelength discriminator, the output curve **190** would be

$$P(normalized) = \left[\frac{P\,det(a) - \{P\,det(b) + P\,det(c)\ \ldots + P\,det(n)\}}{P\,det(a) + \{P\,det(b) + P\,det(c)\ \ldots + P\,det(n)\}}\right]$$

Where

Pdet(a)=output power from excited channel

Pdet(b) through Pdet(n)=output power from non-excited channel.

A lookup table constructed from the values of curve **190** would produce the value for $\lambda_1$=1300 nm as shown at point **196**. Similarly, when second source **144** excites grating **150**, wave energy at the exemplar wavelength $\lambda_2$=1305 nm would return through splitter **146**, fiber **173**, and now fiber **174** would contain the response shown in plot **186**. Fibers **168** and **180** would contain wave energy shown in plot **188**, corresponding to point **200**. The normalized power ratio for $\lambda_2$=1305 nm is represented by point **204** of the plot **190**. The case where third source **154** excites grating **160** is shown in third detector response **186**, and first and second detector responses **188**. For the case where third grating wavelength is 1310 nm, the responses of the third detector, first and second detectors, and normalized power ratio are shown in points **206**, **208**, and **210**. It is clear to one skilled in the art that this system is extendable to n ports of measurement, where each port has a source, a splitter, and each splitter port is connected to an input port of an n-way wavelength discriminator. Each output port of the n-way wavelength discriminator is coupled to a detector, and the response of each detector is measured, and the normalized power ratio is formed from the ratio of the difference between the response of an excited port and the responses of all of the non-excited ports, divided by the sum of all of the responses of excited and non-excited ports.

FIG. **10** shows a strain/temperature sensor system **211** attached to a fiber **220** comprising a plurality of gratings **224**, **226**, and **230**. These sensors operate as earlier described, but are sequentially applied to various parts of a fiber **220**. Each sensor **224**, **226**, and **230** reflects wave energy at respective unique wavelengths $\lambda_1$, $\lambda_2$, and $\lambda_n$. Since gratings **224** and **226** have no effect on out-of-band waves at $\lambda_n$, splitter **218** delivers to fiber **268** the superposition of reflected unique wavelengths $\lambda_1$ through $\lambda_n$. Wavelength separator **236** has broadband outputs which respond only to the range of reflected wavelengths for that given output. For example, output **235** is responsive only to the range of $\lambda_1$, and output **243** is only responsive to the range of $\lambda_2$, and output **249** is only responsive to the range of $\lambda_n$. This requires that the sensor wavelengths and wavelength separator characteristics be chosen such that isolated response of a given wavelength separator to a given sensor grating wavelength occur. In this manner, output **235** represents exclusively the range of wavelengths of sensor **224**, output **243** represents exclusively the range of wavelengths of sensor **226**, and output **249** represents exclusively the range of wavelengths of sensor **230**. The conversion of the outputs of separator **236** into a detected wavelength occurs as was earlier described in FIGS. **4**, **5**, and **6**. In this manner, multiple sensors can share a single fiber, as long as each produces a unique wavelength.

An alternate wavelength measurement apparatus **318** is shown in FIG. **11**, which performs the same function as **270** of FIG. **10**. While the wavelength measurement apparatus **270** uses a wavelength separator **236** followed by narrowband wavelength discriminators **234**, **242**, and **248**, the wavelength measurement apparatus **318** of FIG. **11** utilizes a broadband wavelength discriminator **316** followed by wavelength separators **312** and **314**. These produce complimentary outputs **296** and **304** for $\lambda_1$, complimentary outputs **298** and **306** for $\lambda_2$, and complimentary outputs **300** and **308** for $\lambda_n$. Detectors **232**, **240**, **246**, **238**, **244**, and **250** operate in a manner identical to those of FIG. **10**.

FIG. **12** shows a measurement system **340** connected to fiber **350**, which has a series of sensors **352**, **354**, and **358**, which operate the same as those described earlier in FIG. **10**. A single broadband source excites fiber **350** through splitter **348**. Splitter **348** returns aggregate reflected waves from sensors **352**, **354**, and **358** on fiber **356**. A series of tunable filters **362**, **364**, and **368** is coupled to detector **360**. Each of these filters is tuned over a narrow range through the application of a control voltage **372**, **374**, and **378**. In operation, filters **364** and **368** have a voltage applied which reflects wave energy out of the range reflected by the sensors **354** and **358**, enabling the passage of waves reflected by sensor **352** to pass through and on to tunable filter **362**. Tunable filter **362** is swept over its tuning range, and produces a minimum output at detector **360** at the point where the grating **352** matches the tuned filter **362**. Controller **380** has the characteristic of tunable filter **362** stored in memory such that the voltage **372** producing a minimum detected output **370** enables the extraction of corresponding wavelength for $\lambda_1$. Next, tunable filters **362** and **368** are tuned out of the band of grating **352** and **358**, and tunable filter **364** is swept over its range until a detector minimum is found. As earlier, this minimum voltage corresponds to the wavelength $\lambda_2$, This process continues for as many sensor gratings and tunable filters that are present in the system. In practice, there are many ways of fabricating tunable gratings, including the application of a material with an index of refraction which varies with an applied voltage, the application of a tensile force to a fiber having a grating, or the application of a magnetic field to a grating in close proximity to a material having an index of refraction which changes with an applied magnetic field. It should be clear to one skilled in the art that there are many different ways of practicing such tunable filters, wherein an applied control voltage changes the wavelength of reflection of the tunable filter.

FIG. **13** shows the waveforms for the system of FIG. **12**. Tunable filter control voltage points **390**, **392**, and **394** correspond to the detector minima **396**, **398**, and **400** shown, and therefore enable the recovery of sensor wavelengths $\lambda_1$, $\lambda_2$, and $\lambda_n$.

While the foregoing description is drawn to specific implementations, it is clear to one skilled in the art that other embodiments are available. For example, the earlier described functions SUM and DIFF, which relate to the normalized power ratio, could be implemented using operational amplifiers computing these measurements as analog values, or they could be implemented digitally, operating on digitized detector values, These converters could be either integral to the microprocessor, or external, and the sum and difference values could either be computed through direct reading of the values of the detectors, or through reading sum and difference voltages of alternate circuitry. While the multiple sensor system of FIGS. **10** and **12** are drawn to a 3 sensor system, it is clear to one skilled in the art that these could be drawn to arbitrary numbers of channels operating as strain sensors, temperature sensors, or both. There are also many ways of extracting sensor wavelength from the systems described. For clarity, time division processing has been shown, wherein at a particular time, only a single channel of the system is active, and only one particular wavelength value is recovered. In addition to the explicitly described method of time division processing, there are many modulation schemes wherein each of the sensor values is modulated in frequency or amplitude, and later demodulated to recover the desired value. In this manner, all of the channels of the system could operate simultaneously, rather than sequentially. The use of specific examples for illustration and understanding of the operation of the system does not imply an exclusive manner in which these systems could be implemented.

FIG. **14** shows a strain/temperature measurement system **20** similar to that of FIG. **2**, but with a different wavelength discriminator. In the alternate embodiment of FIG. **14**, the elements having the same numbering as those of FIG. **2** perform the same function as earlier described, but the wavelength discriminator now comprises third splitter **400** which has as inputs the previously described fibers **41** and **43**, and has a normalizing output **406** which is wavelength-invariant compared to wavelength determining output **405**. The wavelength-determining output **405** is formed from broad-bandwidth grating **404**, which has an output amplitude varying with wavelength over the tuning range of the sensor gratings, as will be described later. First detector **408** and second detector **410** accept optical inputs **405** and **406**, respectively, and produce electrical outputs **412** and **414** which are proportional to the respective optical inputs **405** and **406**.

FIG. **15** shows the controller **401** of FIG. **14**, which is similar to the controller of FIG. **3**, and has similarly-functioning elements numbered the same as those of FIG. **3**, as was described earlier. First detector output **412** drives buffer **416** and produces output **420**, which is digitized by analog-digital converter **424** and is presented as a digital input **428** to microprocessor **78**. Second detector output **414** drives buffer **418** to produce signal **422** which is converted to a digital input **430** by analog-digital converter **426** and delivered to microprocessor **78**.

FIG. **16** shows the characteristic response of the wavelength discriminator having a normalizing input **406**, represented by response curve **464**, and wavelength-determining input **405**, represented by response curve **450**. As the reflected wave from grating **46** or grating **52** passes through third splitter **400**, equal amounts of energy are presented into grating **404**, and to normalizing input **406**. As the wavelength applied to third splitter **400** is varied, normalizing output **406** follows the response of curve **464**, while the wavelength-determining input **405** follows the response of curve **450**, in accordance with the characteristic response of broadly tuned grating **404**, whose characteristics are chosen to include a monotonic region from first discrimination wavelength **452** to final discrimination wavelength **454**. In the case where grating **46** is reflecting a wavelength of 1306 nm, curve **460** represents the spectral energy of reflected energy from grating **46**, which is applied to curve **460** to produce an output of approximately 1.0 units. This same reflected response **456**applied to grating **404** having the response of curve **450** and produces an output of approximately 0.25 units. As can be seen from FIG. **16**, as long as the range of input wavelength is between first discrimination wavelength **452** and final discrimination wavelength **454**, it is possible to recover the wavelength from curve **450**. By using the ratio of response **450** to response **464**, the effect of intensity variations in first source **36** and second source **40** is removed, as was discussed for the system of FIG. **2**. By keeping a copy of the characteristic curve of this normalized function of curve **450** divided by curve **464** in the microprocessor **78**, it is possible to resolve any input wavelength in the range first discrimination wavelength **452** to final discrimination wavelength **454** when given the first detector output **412** and second detector output **414**. As described earlier, this determination can be made by storing the response of curves **450** and **452** in a look-up table, or by specifying the curve as the coefficients of a polynomial, or in many other ways, all of which form representations of the characteristic curves of **450** or the ratio of curve **450** divided by curve **452**.

FIG. **17** shows another embodiment **503** of a temperature/strain sensor comprising the old elements of FIG. **2** with a new wavelength discriminator circuit. This new wavelength discriminator comprises third splitter **470**, fourth splitter **488**, a coarse wavelength discriminator **474**, and a fine wavelength discriminator **492**, coarse wavelength first and second detectors **478** and **484**, and fine wavelength discriminator first and second detectors **504** and **498**. The operation of the coarse wavelength discriminator comprising coarse wavelength discriminator **474**, first detector **478**, and second detector **484** is similar to that described in FIGS. **4**, **5**, and **6**, and has a usable wavelength range matched to that of the sensor grating operating range. However, in addition to the coarse wavelength discriminator, a fine wavelength discriminator comprising fine wavelength discriminator **492**, and first detector **504** and second detector **498** are used. Third splitter **470** and fourth splitter **488** produce the signals for simultaneous delivery to the coarse and fine wavelength discriminators, as all 4 detectors are used simultaneously, although as described earlier, the first source **36** and second source **40** operate during different intervals, or have orthogonal modulation functions which enable the discrimination of the two detector outputs through the use of a modulation function applied to the sources and a demodulation function applied to the detectors.

FIG. **18** shows the details of the fine and coarse wavelength discriminators. Curves **516** and **510** represent the optical response of the wavelength discriminator, as measured at fibers **476** and **482**, as well as the detected electrical responses of **480** and **486** to changes in wavelength of sensor **46** or **52**, all of which function as earlier described in the system of FIG. **2**. For the case of sensor **46** reflecting optical energy at 1302 nm, fiber **472** carries optical wave energy which is provided to coarse wavelength discriminator **474**. First output optical fiber **476** carries the energy of curve **512**, while second output optical fiber **482** carries the energy of curve **514**. Fine wavelength discriminator **492** has many more cycles in the same monotonic range of coarse wavelength discriminator **474**, as is seen by the periodicity of curves **510** and **516** of the coarse wavelength discriminator, compared to curves **522** and **524** of the fine wavelength discriminator. The monotonic curve of **510** and **516** is necessary over the tuning range of the reflecting gratings **46** and **52** to ensure single-wavelength resolution. The multiple cycles of discriminator **522** and **524** enable the more precise measurement of wavelength when used in combination with the coarse wavelength discriminator **474**. Fine wavelength discriminator is fed by fiber **491**, and has a first output **502** which carries the energy of curve **522** and a second output **496** which carries the energy of curve **524** when excited by the signal of fiber **491**. When the input signal is provided by fiber **493**, the characteristic of the first and second outputs reverse, as was described earlier in FIGS. **4**, **5**, and **6**. In this manner, sensor **46** reflecting a 1302 nm wavelength produces a first coarse detector response of **512**, a second coarse detector response of **514**, a first fine detector response of **526**, and a second fine detector response of **528**. Sensor **52** reflecting a wavelength of 1311 nm produces a first coarse detector response of **518**, a second coarse detector response of **520**, a first fine detector response of **532**, and a second fine detector response of **530**. As is clear to one skilled in the art, any combination of curve storage methods for maintaining the characteristic curves of **510**, **516**, **522**, and **524** or the difference divided by the sum of curves **510** to **516**, or curves **522** and **524** could be stored using the previously described look-up tables, polynomial coefficients, or interpolated points for use by the microprocessor **78** of the controller **501** of FIG. **17**.

FIG. **19***a* shows the block diagram for a temperature measurement system **600**, comprising a temperature/strain sensor **604**, and measurement system **602**. FIG. **19***a* is best understood in combination with FIGS. **20***a*, **20***b*, **20***c*, **20***d*, and **20***e*, which show the wavelength specific behavior of the system. For FIGS. **20***a* through **20***f*, the x-axis wavelength range is the same for all figures for ease of understanding. Temperature/strain sensor **604** comprises a series of gratings applied to a single fiber, each grating reflecting incoming optical energy at a unique wavelength which defines a wavelength channel, and the wavelength ranges of each grating are chosen such that a single grating operates within a wavelength channel, and no two wavelength channels overlap each other. Wavelength channels are shown in FIG. **20***a*, **20***b*, **20***c*, and **20***d* as **701**, **703**, **705**, and **707**, centered about $\lambda_1$, $\lambda_2$, $\lambda_3$, and $\lambda_n$, respectively, and are common to FIGS. **20***a*–**20***d*. As can be seen, each grating is operating within its own wavelength channel, and no two gratings are ever reflecting wave energy at the same wavelength. Gratings **606**, **608**, **610**, and **612** are shown as the **4** gratings at wavelengths $\lambda_1$, $\lambda_2$, $\lambda_3$, and $\lambda_n$, respectively, however the number of gratings could be as small as one or two, and as large as the number of wavelength channels which can be supported in the system, and could be greater than many hundreds. As an example of wavelength resolution, where gratings **606** and **608** are operating in adjacent wavelength channels **701** and **703**, respectively, the highest wavelength reflected by grating **606** and the lowest wavelength reflected by **608** would be unique and distinguishable, as they are operating in separate wavelength channels. In addition, a depolarizer **607** may be placed in series with the optical path by putting the depolarizer either in the measurement sensor **604**, or in the measurement system **602**. The function of the depolarizer **607** is to remove any polarization provided by the source **614**, or the reflected optical energy of the gratings **606**, **608**, **610**, **612** of the sensor **604**. The depolarizer **607** may be placed in series anywhere in the return optical path **622***a*, **622***b*, or individually at **628** and **650**, however the placement on **623***a* or **623***b* provides two-way depolarization, and is believed to be the best mode of the invention. Optionally, the depolarizer may be either present or absent from the system in the locations provided. One source of depolarizer is the IDP series from Alliance Fiber Optic Products of Sunnyvale, Calif.

Measurement system **602** comprises a broadband optical source **614** which has optical output which covers all wavelength channels of the sensors **606** through **612**. The broadband nature of this source is shown as the curve **700** of FIG. **20***a*, which does not vary with wavelength in the best mode, although a wavelength-dependant wavelength source could be used. The number of sensors supported is determined by the number of wavelength channels and the wavelength bandwidth of each channel. Hence the source **614** must provide optical energy of sufficient bandwidth to cover all of these channels, although the variation of optical output versus wavelength within a single channel need not be carefully controlled, as will be seen. Broadband optical energy leaving source **614** travels to a first splitter **616**, which provides optical energy **618** to the temperature-strain sensor assembly **604**. Narrowband optical energy **620** reflected by each sensor is then delivered back to first splitter **616**, where it divides evenly into a reference path **650** and a comparison path **626**. In one embodiment, the two paths **650** and **626** represent evenly divided optical energy from the output **622** of first splitter **616**, however it is possible to accommodate splitter distributions other than 50:50, such as 60:40, etc. Sine filter **628***a* is coupled on path **626** to the comparison output of second splitter **624**, and the sine filter **628***a* has the characteristic of operating over each wavelength channel, producing an output which is either minimal or maximal at one end of the wavelength channel and maximal or minimal, respectively, at the other range of the wavelength channel. This transfer function reverses and repeats for each wavelength channel over the entire range of operation of the measurement system. Curve **710** of FIG. **20***b* shows the transfer function of the sine filter, which has an output amplitude which varies with wavelength. The transfer function behavior is periodic over two adjacent wavelength channels. There are two coarse WDM (wavelength division multiplex) filters **630** and **652**, which in the best mode have identical filtering characteristics, where this filtering characteristic is to provide coarse separation of wavelength output based on wavelength channel. There are as many outputs for each coarse WDM filter **630** and **652** as there are n wavelength channels in the system.

FIG. **20***c* shows the transfer function for each coarse WDM filter. For illustration and in understanding the operation of the coarse WDM filter, when a broadband source is applied to the WDM filter input, such as source **760**, each output produces output wavelengths specific to a particular wavelength channel. For example, outputs **633** and **643** of FIG. **19** could filter and provide exclusively wavelength channel **1** optical response of sensor **606**. Since coarse WDM filter **662** is acting only on optical energy without the effect of the sine filter **628***a*, it provides a reference output constant with wavelength, while the comparison WDM filter **652** provides an output which includes the effect of the sine filter **628***a* and varies with wavelength. Outputs **635** and **645** would exclusively provide the wavelength channel **2** optical response of sensor **608**, and analogous behavior would be shown by outputs **637**, **647**, **639**, and **649**, and sensors **610** and **612** respectively. Each comparison and reference WDM filter has an output associated with a particular wavelength channel, and each WDM filter output is coupled to an optical detector, which converts an optical input to an electrical output. Each such reference and comparison detector forms a detector pair operating within each wavelength channel. A controller **640** is coupled to each detector electrical output, and reads the detector outputs in pairs. In the example system of FIG. **19**, wavelength channel one pair responsive to sensor **606** could be reference detector **642** and comparison detector **632**. Other reference and comparison detector pairs for sensors **608**, **610**, and **612** are **644** & **634**, **646** & **636**, and **648** & **638** respectively.

FIG. **20***d* shows the optical energy provided to each WDM filter, and the outputs produced by each detector. Reflected optical energy **620** has been transferred through first splitter **616** to second splitter **624** via path **622**, and is divided evenly between sine filter **628***a*, which provides filtered optical energy to comparison WDM filter **630** and reference WDM filter **652**. First reference detector **642** receives reference optical energy **720**, which represents energy reflected by grating **606**. The sine filter transfer function of sine filter **628***a* is shown as curve **721** of FIG. **20***d*. Comparison detector **632** receives filtered optical energy, shown by curve **722**. As was described in earlier figures, the ratio of power between comparison detector **642** exposed to optical power **722** and reference detector **632** exposed to optical power **723** forms a monotonically varying factor which may be used to formulate a mathematical relationship between temperature or strain. This translation between detector power ratio and wavelength/strain may be done in controller **640** using a best-fit curve, or a look-up table, or any other method known to one skilled in the art. Curve **20***d* also shows wavelength channel **703** responding to sensor **608** and having reference detector response **724** with comparison detector response **726**, wavelength channel **705** responding to sensor **610** and having reference detector response **728** and comparison detector response **730**, and wavelength channel **707** responding to sensor **612** and having reference detector response **732** and comparison detector response **734**.

FIG. **20***e* shows the operation of a single sensor **606** operating in wavelength channel **701**. At the center of the range **752**, there is a wavelength λb reflected by the sensor **606** where the reference detector **642** provides an output based on response to **742** from the reference WDM filter, and comparison detector **632** provides an output based on response to **744** from the comparison WDM filter. The ratio of comparison detector to reference detector is roughly 0.5 for wavelength λb. As either the strain increases or temperature rises on sensor **606**, the grating pitch increases, thereby increasing the sensor wavelength of reflection to **754** λc, and producing reference detector input **746** and comparison detector input **748**, which produces a ratio of comparison detector to reference detector of roughly 0.125 for λc. When either the strain decreases or temperature reduces on sensor **606**, the grating pitch decreases, thereby reducing the wavelength of response to **750** λa, and producing reference detector input **738** and comparison detector input **740**, which produces a ratio of comparison detector to reference detector of roughly 0.85 for λa. In this manner, the ratio of comparison detector to reference detector is computed, and this ratio is used to produce either a temperature or a strain for the associated sensor. Each sensor operates independently of the other sensors, so the sensors may be placed in any location or in any order on the sensor assembly **604**. While the system is shown for four sensors, it is clear to one skilled in the art that the system may be reduced to one or two sensors, or expanded to hundreds of sensors based on the description and figures disclosed herein.

FIG. **19***b* shows circulator **616***b* which can be used in place of first splitter **616***a*, where the port functions and mappings are identical to those shown in FIG. **19***a*. Circulator **616***b* accepts an optical signal on port **621***b* and delivers it to port **623***b*. Reflected energy returning on port **623***b* is directed to port **622***b*, and continues on to the measurement system, as was detailed in FIG. **19***a*. The first splitter **616***a* of FIG. **19***a* exhibits a 3 db loss from **621***a* to **623***a*, and an additional 3 db loss from **623***a* to port **622***a*, so the overall insertion loss is in excess of 6 db. The circulator **616***b* exhibits a 1 db port to port insertion loss, so the overall insertion loss is only 2 db, and is less than the 3 db per path insertion loss of the previously described splitter **616***a*.

FIG. **19***c* shows a calibrating sine filter **628***b* which replaces the sine filter **628***a* of FIG. **19***a*. The purpose of the sine filter with complementary outputs is to characterize the background broadband reflections of the sensors through the calibration process. These reflections produce sensor-dependant background levels of optical energy, which appear as DC offsets in the detectors. The system of FIG. **19***a* is susceptible to variations in the offset values produced by the detector **632**, **634**, **636**, **638** compared to their complementary counterparts **642**, **644**, **646**, **648**. A detector offset between the complementary detector pair **632** and **642**, for example, would result in an error in computation of power ratio as described earlier. One means of correcting for this would be to periodically switch the sine filter **628***a* from the input of wdm filter **630** to the input of wdm filter **652**. An alternate method is to use the complementary sine processor **628***b*. In the embodiment shown in FIG. **19***c*, input **626***b* is split into sine output and sine complementary outputs **658** and **660** respectively by complementary sine filter **664**, which has a complementary response which varies with wavelength according to FIG. **20***f* curves **776** and **774**, respectively. Optical switch **656** selects between outputs **658** and **660** according to a signal provided by the controller **640**, and delivers the selected signal to the coarse wdm filter **630**. When the switch selects output **658**, the operation is the same as using sine filter **628***a*. However, when the switch selects output **660**, offsets associated with the detectors **632**, **634**, **636**, **638** coupled to wdm filter **630** may be determined and cancelled.

The system is also resistant to variation in system components. For example, since the wavelength is computed from a power ratio, variations in source power over time, temperature, or wavelength are normalized out of the computed ratio. Specific characteristics of the second splitter and sine filter may be stored as values specific to a single measurement system to accommodate a wide range of splitters and sine filters. While the system is shown for an embodiment of 4 sensors, it is clear that the system can be expanded or reduced to an arbitrary number of sensors. In general, for a system with n sensors, there are n gratings applied to sensor **604**, and the reference and comparison WDM filters have n outputs coupled to n detector pairs. Each sensor and WDM filter operates in its own unique wavelength channel, and the sine filter transmission response in each of these channels is single valued, which is to say it is either monotonically increasing or monotonically decreasing across the wavelength range of a single wavelength channel.

We claim:

**1**. A fiber-optic sensor system comprising: a sensor assembly, said sensor assembly comprising a plurality n of gratings applied to a single fiber, said sensor assembly having a single port, said sensor assembly port returning optical energy in a wavelength unique to each said n grating when optical energy is applied to said single port:

a sensor controller comprising:

a broadband optical source coupled to a first splitter, said first splitter having a sensor port, a measurement port, and a source port coupled to said broadband source, said first splitter coupling optical power from said broadband source to said sensor port, and coupling optical power from said sensor port to said measurement port;

a second splitter having an input port, a comparison port, and a reference port, optical power applied to said input port splitting between said comparison port and said reference port, said second splitter input port coupled to said first splitter measurement port;

a sine filter having an input port and an output port, the transfer function of said sine filter being an attenuation function which varies periodically over a range of wavelengths, said sine filter coupled to said second splitter comparison port;

a reference WDM filter and a comparison WDM filter, each said WDM filter having an input port and a plurality said n of output ports, each said output port responsive to a wavelength associated with each said n sensor, said comparison WDM filter input coupled to said sine filter output, and said reference WDM filter input coupled to said second splitter reference port;

a plurality said n of detector pairs, each said detector pair coupled to said reference WDM filter output port and said comparison WDM filter output port and providing a reference output and comparison output for each said sensor;

a controller coupled to each said n plurality of detector pairs, converting a reference output and comparison output into an associated sensor measurement for each said n plurality of detector pairs.

**2**. The fiber-optic sensor system of claim **1** where said first splitter is an optical splitter having a pair of first ports and a pair of second ports, whereby optical energy coupled to either of said splitter first ports divides evenly into said pair of second ports, and energy coupled to either of said splitter second ports divides evenly between said splitter first ports.

**3**. The fiber-optic sensor system of claim **2** where the optical energy removed from at least one of said second ports is at least 3 db lower than the optical energy applied to said first port.

**4**. The fiber-optic sensor system of claim **2** where the optical energy removed from at least one of said first ports is at least 3 db lower than the optical energy applied to said second port.

5. The fiber-optic sensor system of claim **1** where said first splitter is an optical circulator having a first port for the introduction of first optical energy, a second port for the introduction of second optical energy, said second port also removing said first optical energy applied to said first port, and a third port for removal of said second optical energy applied to said second port.

6. The fiber-optic sensor system of claim **5** where the optical path loss from said first port to said second port is less than 3 db.

7. The fiber-optic sensor system of claim **5** where the optical path loss from said second port to said third port is less than 3 db.

8. a fiber-optic sensor system comprising: a sensor assembly, said sensor assembly comprising a plurality n of gratings applied to a single fiber, said sensor assembly having a single port, said sensor assembly port returning optical energy in a wavelength unique to each said n grating when optical energy is applied to said single port;

a sensor controller comprising:

a broadband optical source coupled to a first splitter, said first splitter having a sensor port, a measurement port, and a source port coupled to said broadband source, said first splitter coupling optical power from said broadband source to said sensor port, and coupling optical power from said sensor port to said measurement port;

a second splitter having an input port, a comparison port, and a reference port, optical power applied to said input port splitting between said comparison port and said reference port, said second splitter input port coupled to said first splitter measurement port;

a switchable sine filter having:

an input port and an output port, said input port coupled to a complementary sine filter having a sine output and a complementary sine output, said sine output and said complementary sine output having a response which vary in a complementary manner as the wavelength applied to said sine filter input port is varied;

an optical switch having a first selector input coupled to said sine output, a second selector input coupled to said complementary sine output, a selector output coupled to said switchable sine filter output port, and a control input which causes said selector output to couple to either said sine filter input port or said sine filter complementary sine output port, said sine filter input coupled to said second splitter comparison port;

a reference WDM filter and a comparison WDM filter, each said WDM filter having an input port and a plurality said n of output ports, each said output port responsive to a wavelength associated with each said n sensor, said comparison WDM filter input coupled to said switchable sine filter output, and said reference WDM filter input coupled to said second splitter reference port;

a plurality said n of detector pairs, each said detector pair coupled to said reference WDM filter output port and said comparison WDM filter output port and providing a reference output and comparison output for each said sensor;

a controller coupled to each said n plurality of detector pairs, converting a reference output and comparison output into an associated sensor measurement for each said n plurality of detector pairs, said detector producing an output coupled to said switchable sine filter optical switch control input.

9. The fiber-optic sensor system of claim **8** where said first splitter is an optical splitter having a pair of first ports and a pair of second ports, whereby optical energy coupled to either of said splitter first ports divides evenly into said pair of second ports, and energy coupled to either of said splitter second ports divides evenly between said splitter first ports.

10. The fiber-optic sensor system of claim **8** where the optical energy removed from at least one of said second ports is at least 3 db lower than the optical energy applied to said first port.

11. The fiber-optic sensor system of claim **8** where the optical energy removed from at least one of said first ports is at least 3 db lower than the optical energy applied to said second port.

12. The fiber-optic sensor system of claim **8** where said first splitter is an optical circulator having a first port for the introduction of first optical energy, a second port for the introduction of second optical energy, said second port also removing said first optical energy applied to said first port, and a third port for removal of said second optical energy applied to said second port.

13. The fiber-optic sensor system of claim **8** where the optical path loss from said first port to said second port is less than 3 db.

14. The fiber-optic sensor system of claim **8** where the optical path loss from said second port to said third port is less than 3 db.

15. The fiber-optic sensor system of claim **1** where said first splitter includes a depolarizer filter placed in series with said first splitter sensor port.

16. The fiber-optic sensor system of claim **8** where said first splitter includes a depolarizer filter placed in series with said first splitter sensor port.

* * * * *